AD-A106 422 COLORADO STATE UNIV FORT COLLINS DEPT OF FOREST AND --ETC F/G 17/5
THERMAL VEGETATION CANOPY MODEL STUDIES.(U)
AUG 81 J A SMITH, K J RANSON, D NGUYEN DACW39-77-C-0073

UNCLASSIFIED WES/TR/EL-81-6 NL

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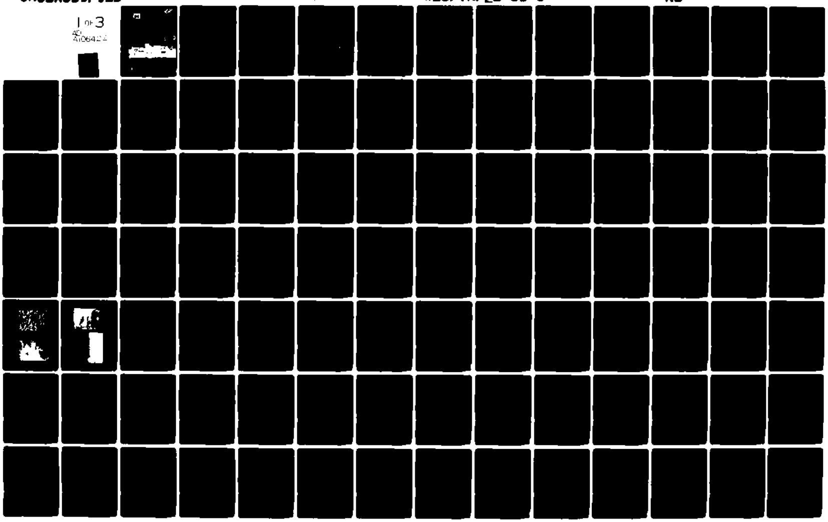

LEVEL II

TECHNICAL REPORT EL-81-6

THERMAL VEGETATION CANOPY MODEL STUDIES

by

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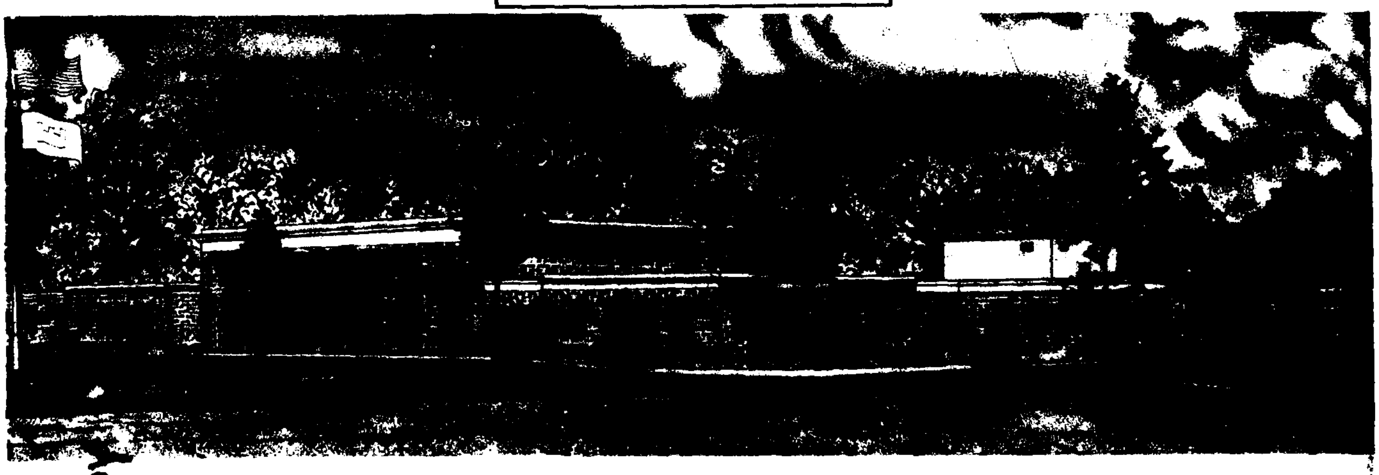
August 1981

Final Report



Prepared for Headquarters, Department of the Army
Washington, D. C. 20314

Under Project No. 4A762730AT42, Task A4, Work Unit 003
(Contract No. DACW 39-77-C-0073)

Monitored by Environmental Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: Technical Report EL-81-6	2. GOVT ACCESSION NO.: AD-A106 422
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): THERMAL VEGETATION CANOPY MODEL STUDIES	5. TYPE OF REPORT & PERIOD COVERED: Final report
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): J. A. Smith, K. J. Ranson, D. Nguyen, and L. E. Link	8. CONTRACT OR GRANT NUMBER(s): DACW 39-77-C-0073
9. PERFORMING ORGANIZATION NAME AND ADDRESS: College of Forestry and Natural Resources, Colorado State University, Fort Collins, Colo. 80523, and U. S. Army Engineer Waterways Experiment Station, P. O. Box 631, Vicksburg, Miss. 39180	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Project No. 4A762730AT42, Task A4, Work Unit 003
11. CONTROLLING OFFICE NAME AND ADDRESS: Headquarters, Department of the Army, Washington, D. C. 20314	12. REPORT DATE: August 1981
	13. NUMBER OF PAGES: 212
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): U. S. Army Engineer Waterways Experiment Station, Environmental Laboratory, P. O. Box 631, Vicksburg, Miss. 39180	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

James A. /Smith
K. Jon /Ranson
Duong /Nguyen
Lewis E. /Link

17. DISTRIBUTION STATEMENT (of the abstract

18. SUPPLEMENTARY NOTES

Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22151.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Computerized simulation
Infrared detectors
Temperature
Terrain analysis
Terrain models (Analytical)
Thermal measurements
Vegetation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is the final report in a series. Overall objectives of this project are concerned with developing comprehensive optical and thermal signature data bases, the development and evaluation of optical and thermal canopy radiation models, and the interpretation of these measurements. Previous technical reports in this series have described optical and thermal measurements obtained over a coniferous site (Pinus contorta) in Leadville, Colorado. This earlier

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20. ABSTRACT (Continued).

data set served as a test bed for the development and initial evaluation of first, individual components, that is, needle and leaves, thermal models, and then a composite canopy terrain model.

The objectives of the work reported in this study were to evaluate the thermal models developed under a wider range of meteorological conditions and for different vegetation types. In this regard, experiments were performed on a second coniferous site (Pseudotsuga manziesii) near Seattle, Washington, and a deciduous community (oak-hickory) at the Oak Ridge National Laboratory, Tennessee. As part of the evaluation procedure a complete sensitivity analysis was performed for the model. The second major objective of the study reported here was a restructuring of the mathematical model which enabled a factoring of the geometrical characterization of the canopy in terms of matrices which can be convolved with the energy process terms. The newly structured model more easily permits the precalculation of these important geometrical characteristics for a wide variety of terrain elements. Finally, two parameter estimation techniques are proposed for both the static, steady-state, thermal behavior of a canopy and the dynamic or time-dependent implementation.

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PREFACE

The research described in this report was conducted by personnel of the Department of Forest and Wood Sciences, College of Forestry and Natural Resources, Colorado State University (CSU) from 1 October 1978 to 1 February 1980 under contract No. DACW 39-77-C-0073 to the U.S. Army Engineer Waterways Experiment Station (WES). The study was done under Department of the Army Project No. 4A762730AT42, Task A4, Terrain/Operations Simulation, Work Unit 003, Electromagnetic Target Surround Characteristics in Natural Terrains.

Participating project personnel concerned with the tasks described in this report include Dr. James A. Smith, Principal Investigator; Mr. K. Jon Ranson, Research Associate; and Mr. Frank Croft, Graduate Research Assistant. In addition, very significant support was provided by Dr. Duong Nguyen of the Civil Engineering Department. Dr. Lee Balick, on assignment at the WES from CSU, was responsible for the technical review of the report and numerous suggestions that benefited the overall quality of this report.

Experimental data utilized in this study were obtained from a deciduous community at Oak Ridge National Laboratory in conjunction with Dr. B. Hutchison of the Atmospheric Turbulence and Diffusion Laboratory of the National Oceanic and Atmospheric Administration. Similarly, measurements were obtained over a Douglas-fir community in cooperation with Dr. Leo Fritschen of the University of Washington. Thermal imagery was obtained by the Oregon National Guard at the Washington site.

The study was conducted under the general supervision of Dr. John Harrison, Chief of the Environmental Laboratory (EL), and Mr. Bob Benn,

Chief of the Environmental Systems Division, EL. Dr. Lewis E. Link, Chief of the Environmental Constraints Group, EL, was Technical Monitor for the study.

Commanders and Directors of WES during the conduct of this study were COL. John L. Cannon, CE, and COL. Nelson P. Conover, CE. Technical Director was Mr. Fred R. Brown.

This report should be cited as follows:

Smith, J.A., Ranson, K.J., Nguyen, D., and Link, L.E. 1981. "Thermal Vegetation Canopy Model Studies," Technical Report EL-81-6, prepared by Colorado State University in collaboration with the Environmental Laboratory, Waterways Experiment Station, for the U.S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

CONTENTS

THERMAL VEGETATION CANOPY MODEL STUDIES

PART I: INTRODUCTION

1. This technical report is the last of a series of reports prepared on scene radiation dynamics. Earlier volumes in this series have described the development of models for optical and thermal energy interactions with forest and grassland vegetation canopies. Extensive field measurement efforts done in cooperation with the U.S. Army Engineer Waterways Experiment Station (WES) have also been separately reported. This report describes further efforts in thermal model development, evaluation, and sensitivity analysis. Measurements obtained over a Douglas-fir (Pseudotsuga menziesii) experimental site near Seattle, Washington, and an oak-hickory, deciduous site near Oak Ridge National Laboratory, Tennessee, are included. At both sites intensive ground instrumentation was employed as well as thermal overflights provided by the Oregon National Guard and the Georgia National Guard, respectively. In addition, analyses have been performed with data from Zweibrücken Air Force Base in the Federal Republic of Germany.

2. This introduction briefly summarizes the following topics which are explored more fully in the body of the report: (a) model framework, (b) sensitivity analysis, (c) experimental validation, and (d) recommendations.

Model Framework

3. The initial thermal canopy model utilized in this study is described in the report by Kimes, Smith, and Ranson (1979). The model is a plane-parallel abstraction of a vegetation canopy divided into three horizontal layers. Furthermore, steady-state conditions are assumed.

4. An energy-balance formulation of the model may be given in vector form by

$$\underline{F}(\underline{X},\underline{P},\underline{U}) = 0 \qquad (1)$$

where:

$\underline{F} = (F_1\ F_2\ F_3)$ is the energy-balance equation for layers 1, 2, and 3, considering the following energy components: longwave transfers, shortwave transfers, sensible heat, and evapotranspiration

$\underline{X} = (X_1\ X_2\ X_3)^T$ is the average layer temperature vector for layers 1, 2, and 3

$\underline{P} = (\varepsilon_i,\ i=1,2,3\ \ \alpha_i,\ i=1,2,3\ \ \varepsilon_g\ R_l\ \underline{S}\ \underline{A})$ is the parameter vector characterizing the canopy layers

ε_i,α_i = emissivity and absorptivity of the vegetation layer

ε_g,α_g = *emissivity and absorptivity of the ground layer*

R_l = canopy stomatal resistance to water vapor diffusion

$\underline{S}$ = longwave flux transfer matrix calculated from geometrical properties of the canopy

$\underline{A}$ = shortwave flux absorption coefficient vector

$\underline{U} = (T_a\ T_g\ WS\ RH\ SW)^T$ is the control or input vector

T_a = air temperature

T_g = ground temperature

WS = wind speed

RH = relative humidity

SW = shortwave flux

5. As part of the tasks of this project, $\underline{F}$ was rewritten in the following form, which explicitly factors the geometrical properties of the canopy from the remaining energy terms:

$$\underline{F} = \tfrac{1}{2}\,\underline{\alpha\sigma}\;\underline{B}(\underline{X})^{T}\underline{S} + \underline{B}(\underline{X}) + \underline{A} + \underline{H}(\underline{X}) + \underline{LE}(\underline{X}) \qquad (2)$$

where:

σ = Stefan-Boltzmann constant

$\underline{B}$ = vector of longwave emission terms

$\underline{H}$ = vector of sensible heat

$\underline{LE}$ = vector of evapotranspiration term

The significance of this factorization is that a wide variety of abstract or canonical canopies may be characterized by precalculation of $\underline{S}$ and $\underline{A}$ matrices. These matrix tables may then be convolved with the appropriate meteorological driving variables to simulate diurnal behavior for a wide spectrum of scenaries. Five standard canopy structures of three different densities are given. These canopy structure combinations represent a spectrum of geometrical structure-indexed thermal variations. Other combinations may easily be calculated.

6. In addition a view factor matrix $\underline{VF}$ is precalculated for each canopy characterization which is used to calculate thermal exitance $\underline{W}$ as a function of view angle, Θ .

$$\underline{W}(\Theta) = \underline{VF}(\text{Layer},\Theta)\;\underline{B}^{T} \qquad (3)$$

where:

$\underline{W}$ = the predicted canopy exitance at view angle, Θ

7. Finally, a new solution of the energy-balance equation was formulated utilizing the knowledge of the $\underline{F}$ function which permits an explicit evaluation of the Jacobian.

8. Specifically, a modified iterative Newton-Raphson technique is employed (Burden, Faires, and Reynolds 1978).

9. Given $\underline{P}$, $\underline{U}$ for a given time period, $\underline{F}(\underline{X},\underline{P},\underline{U})$ becomes a function of $\underline{X}$ only. Expanding about an initial guess, $\underline{X}_o$, and employing a minimum squared error criteria yields

$$\delta\underline{X} = \underline{X} - \underline{X}_o = (J^T J)^{-1} J^T \, [-\underline{F}(\underline{X}_o)] \quad (4)$$

where:

J = the Jacobian evaluated at $\underline{X} = \underline{X}_o$ and the n+1 iteration is given by

$$\underline{X}_{n+1} = \underline{X}_n + \delta\underline{X} \quad (5)$$

Convergence usually occurs within a few iterations.

10. The initial guess is taken to be air temperature; thus, the solution approach may be interpreted as determining the modification to the air temperature profile which arises when a canopy is inserted into the volume space under consideration.

Sensitivity Analysis

11. A sensitivity analysis was performed on the following parameters and input variables:

α_i longwave absorptivity for vegetation layers 1, 2, and 3

ε_i longwave emissivity for layers 1, 2, and 3

ε_g ground emissivity

R_1 canopy stomatal resistance

A_1 shortwave absorption in vegetation layers 1, 2, and 3

RH relative humidity

T_g ground temperature

WS wind speed

T_a air temperature above the canopy

T_{ac} air temperature within the canopy

Sensitivity analysis was not directly performed on the $\underline{S}$ matrix nor on the view factor matrix. Rather, the above analyses were repeated for two different $\underline{S}$ matrix configurations. One corresponded to the Douglas-fir canopy and the second to an oak-hickory canopy.

12. Sensitivity analysis (Tomovic 1963) involves the evaluation of the sensitivity matrix:

$$\left[\frac{\partial \underline{X}}{\partial \underline{P}}\right]_{\underline{x}_o, \underline{p}_o} = S_{xp} \tag{6}$$

where:

$\underline{X}$ = layer temperature vector

$\underline{P}$ = 16-component parameter/input vector

The analysis was performed in each case for $\underline{x}_o, \underline{p}_o$ corresponding to a daytime and nighttime representative set of conditions.

13. The first order perturbation of each of the 16 parameters was evaluated systematically, solving for the new equilibrium canopy temperature profile after each perturbation, i.e.,

$$\delta \underline{X} = S_{xp} \, \delta \underline{P} \tag{7}$$

The most sensitive parameter of the model was found to be the air temperature within the canopy. Next, dependence on canopy stomatal resistance was found to be highly nonlinear for the low values of R_l. The dependence of canopy temperature on most other parameters was found to be highly linear.

Experimental Validation

14. Comparison of both daytime and nighttime measurements for the Doulgas-fir and oak-hickory canopies with simulation predictions were carried out. For both of the canopies, nighttime simulations deviated from measured values by 2^oC or less. Daytime simulations underestimated measured Douglas-fir canopy temperatures by a maximum of 2^oC; whereas, simulation of the lower canopy for oak-hickory overestimated temperatures by a maximum of 4^oC. Deviation patterns could be explained in terms of macroscopic and variable environmental conditions.

Recommendations

15. Two broad categories of recommendations are made in the enclosed report. First, several suggestions are made relative to improvements that could be made in the thermal model itself. Secondly, some suggested approaches for estimating required parameters in the model from observed data are given.

16. Sensitivity analysis has indicated the importance of the air temperature within the canopy as an input to the model. Further, the validation experiments have indicated the importance of utilizing an appropriate wind speed measurement. Thus, it would appear to be appropriate

to review the various hypotheses concerning the variation in air temperature and wind speed with height. The model is easily modified to include a height dependence of these two variables; they are treated as constants simply because there is not a very strong rationale for choosing among the various options. In a similar vein, various authors' recommendations have been selected for analytic representations of the energy budget components. It may be useful to systematically evaluate several alternative formulations. Two further extensions to the physics of the model would include the incorporation of a ground temperature prediction module and the expansion of the steady-state formulation to a time-dependent process, that is, allowing for heat storage within the canopy.

17. Finally, further analysis of the structure of the geometrical matrices, that is, the $\underline{S}$, $\underline{A}$, and VF matrices, relative to the intrinsic canopy structure variables should be undertaken. Specifically, the possibility of further factoring these matrices in terms of their leaf area index dependence and their dependence upon leaf slope distribution should be investigated. It may be possible to treat the density, that is the leaf area index dependence, as a simple scaling influence on precalculated structural forms. If an analytic decomposition of these matrices in terms of these two influences is not possible, numerical approaches should be investigated. A faster, more tractable, calculation of the shortwave absorption coefficient should be given high priority.

18. Two approaches are recommended for parameter estimation analysis. The first method described is based on the Kalman filtering techniques. The linearization of the model in terms of a classic state-space framework is outlined. A Kalman filtering approach on a parameter vector or an

augmented state vector is described (Friedland 1972). A second approach to parameter estimation is suggested, which is based on the use of sensitivity functions (Durando and Leondes 1976). This approach also begins with a state-space formulation of the model but then proceeds to use the sensitivity functions to calculate an unknown parameter vector by minimizing the square of the error vector between predicted and measured response.

19. The appendixes of this report include the program listings for the thermal model, the sensitivity program, the geometrical preprocessing programs, SCALC, and the SRVC absorption model. Also included in the appendixes are the geometrical matrices for 15 abstract canopies, the sensitivity results, and supporting validation data.

PART II: NEW MODEL STRUCTURE

20. This part summarizes the updated formulation and solution approach to the basic thermal canopy model developed under previous efforts. The individual expressions for the component energy budget processes are summarized and explicit expressions for the elements of the Jacobian matrix are given. The geometrical factorization of the energy budget equation, particularly for the longwave flux transfers, is derived, and the sequence of computer programs required to develop a thermal simulation is described.

Energy-Balance Framework

21. The model is a plane-parallel abstraction of a vegetation canopy divided into three horizontal layers. Two additional source layers are given by the atmosphere above the canopy and by the underlying ground or understory layer. An energy-balance framework, assuming steady-state conditions, is formulated for each of the three vegetation layers (sinks) as a function of the five source layers. For this and subsequent sections Figure 1 may prove useful for conceptualizing the various energy flows. The sink or vegetation layers are represented by $i = 1,2,3$; $j=1,2,3,4,5$ represents, respectively, the atmosphere, the three vegetation layers, and the ground source layers of energy flux. The combination of the i,j indices, thus represents a flow of energy from source layer j to sink layer i.

22. The vector expression for the energy-balance equations was given in the Part I, Equations 1 and 2 as:

$$\underline{F} = \tfrac{1}{2}\,\underline{\alpha\sigma}\;\underline{B}(\underline{X})^T\underline{S} + \underline{B}(\underline{X}) + \underline{A} + \underline{H}(\underline{X}) + \underline{LE}(\underline{X})$$

23. The vector equation may be expanded in long form and the explicit dependence on parameters or input variables indicated by

$$\tfrac{1}{2}\,\alpha_1\sigma\left[B(T_a)S_{11} + B(X_1)S_{12} + B(X_2)S_{13} + B(X_3)S_{14} + B(T_g)S_{15}\right] \quad (8)$$
$$+ A_1 - \sigma B(X_1) + H(X_1;WS,T_a) + LE(X_1;WS,T_a,R_1,RH) = 0$$

$$\tfrac{1}{2}\,\alpha_2\sigma\left[B(T_a)S_{21} + B(X_1)S_{22} + B(X_2)S_{23} + B(X_3)S_{24} + B(T_g)S_{25}\right] \quad (9)$$
$$+ A_2 - B(X_2) + H(X_2;WS,T_a) + LE(X_2;WS,T_a,R_1,RH) = 0$$

$$\tfrac{1}{2}\,\alpha_3\sigma\left[B(T_a)S_{31} + B(X_1)S_{32} + B(X_2)S_{33} + B(X_3)S_{34} + B(T_g)S_{35}\right] \quad (10)$$
$$+ A_3 - \sigma B(X_3) + H(X_3;WS,T_a) + LE(X_3;WS,T_a,R_1,RH) = 0$$

where the explicit formulation for each energy budget component used in the model is given by

Longwave: $$B(X_i) = \varepsilon_i(X_i + 273)^4 \quad (11)$$

$$B(T_a) = \varepsilon_a(T_a + 273)^4 \quad (12)$$

$$B(T_g) = \varepsilon_g(T_g + 273)^4 \quad (13)$$

Sensible Heat: $$H(X_i WS,T_a) = (X_i - T_a)\;\; -0.698(20.4 + 0.2WS^{0.97}) \quad (14)$$

Evapotranspiration:

$$LE(X_i;WS,T_a,R_1,RH) = -697.75(-0.566\,X_i + 597.3)$$

$$\times\,\frac{(5.234\,e^{0.056715\cdot X_i} - RH\,5.234\,e^{0.056715\cdot T_a})\,10^{-6}}{R_1 + 1/60\,(0.04 + 1.27\,WS^{-1/2})} \quad (15)$$

Shortwave absorption: $$A_i = ABS(i)\cdot SW \quad (16)$$

where:

$$\varepsilon_{air} = 1 - 0.261\,e^{-7.77\,\cdot\,10^{-4}T_a^{\,2}} \quad (17)$$

ABS(i) = shortwave absorption coefficients calculated by an optical absorption model which uses a Monte Carlo Technique to include multiple scattering effects (see Program SRVC in Appendix A)

Explicit Evaluation of the Jacobian

24. As indicated in Part I, the use of the iterative Newton-Raphson technique for solving the nonlinear thermal equations involves repeated evaluation of the expression

$$\delta \underline{X} = (J^T J)^{-1} J^T [-\underline{F}(X_o)] \tag{18}$$

where:

$$J = \text{system Jacobian} = \left[\frac{\partial \underline{F}}{\partial \underline{X}} \right] X = X_o \tag{19}$$

The Newton-Raphson method is employed because, in this case, there are relatively simple closed-form expressions for the elements of $\underline{F}$, and the Jacobian matrix can explicitly be evaluated. Specifically,

$$\underline{J} = \begin{vmatrix} \frac{\partial F_1}{\partial X_1} & \frac{\partial F_2}{\partial X_1} & \frac{\partial F_3}{\partial X_1} \\ \frac{\partial F_1}{\partial X_2} & \frac{\partial F_2}{\partial X_2} & \frac{\partial F_3}{\partial X_2} \\ \frac{\partial F_1}{\partial X_3} & \frac{\partial F_2}{\partial X_3} & \frac{\partial F_3}{\partial X_3} \end{vmatrix} \tag{20}$$

The i,j component of $\underline{J}$ is easily derived as

$$J_{ij} = 2 \alpha_i \varepsilon_j S_{ij} \sigma(X_j + 273)^3 + \delta_{ij} \{4\varepsilon_j \sigma(X_j + 273)^3 + 0.698 T_a$$

$$(20.4 + 0.2WS^{0.97}) + \frac{(697.75)(0.566)(5.234)(10^{-6})(e^{0.056715 X_j} - RH\, e^{0.056715 T_a})}{R_1 + 1/60 (0.04 + 1.27 WS^{-0.5})} +$$

$$\frac{-(697.75)(-0.566 X_j + 597.3)(5.234)(0.056715) 10^{-6} e^{0.056715 X_j}}{R_1 + 1/60 (0.04 + 1.27 WS^{-0.5})} \tag{21}$$

where:

δ_{ij} = Dirac delta function

25. Program TMODEL, which implements the equations, is given in Appendix A. Subroutine FEVAL evaluates the function and the Jacobian derivatives and calls upon Subroutine BFUNC which calculates the longwave energy component and derivative; Subroutine QFUNC calculates the sensible heat component and derivative. It should also be noted that two different expressions for the convection coefficient arise, depending upon the ambient wind speed. Subroutine RFUNC calculates the evapotranspiration.

Geometrical Factorization

26. A significant simplification of the thermal model employed in this study was the factorization of the geometric-dependent terms from the energy-related terms for the longwave flux transfer processes. This factorization is made possible essentially because of the lack of multiple scattering in the thermal regime between canopy components whose emissivities (absorptivities) are assumed nearly unity and by the fact that the thermal properties on both sides of a canopy component are assumed equal. The significance of the factorization is not so much in the increased efficiency in model calculation as it is in permitting the possibility of precalculating these geometrical matrices, $\underline{S}$, for a wide variety of plant canopies. These precalculated matrices may then be convolved with the appropriate driving variables as required. Program SCALC (Appendix A) performs the actual calculations for given input of geometric measurements.

27. The required input data for a three-layer canopy include

f_{ik} = leaf slope distribution for layer i=1,2,3 and angle Θ_k=5,15,...,85

N_i = leaf area index LAI , for layer i

Appendix B presents the $\underline{S}$ matrices calculated for five different theoretical canopies at three different LAI densities = 1, 4, and 7.

28. The five theoretical canopies are approximated by Verhoef and Bunnik (1975) as

Planopnile: $f_{ik} = \frac{2}{\pi}(1 + \cos 2\,\Theta_k)$

Erectophile: $f_{ik} = \frac{2}{\pi}(1 - \cos 2\,\Theta_k)$

Plagiophile: $f_{ik} = \frac{2}{\pi}(1 - \cos 4\,\Theta_k)$

Extremophile: $f_{ik} = \frac{2}{\pi}(1 + \cos 4\,\Theta_k)$

Uniform: $f_{ik} = \frac{2}{\pi}$

where Θ_k is the leaf slope angle.

The elements of the $\underline{S}$ matrix, itself, are given by

$$S_{ij} = \sum_{k=1}^{9} f_{ik}\, C_{ijk} \tag{22}$$

where:

$$C_{ijk} = \int_0^{\pi/2} \int_0^{2\pi} |\hat{a} \cdot \hat{r}|\ \mathrm{CONT}_{ijr}\, d\phi_r\, d\Theta_r \tag{23}$$

$\hat{a}$ is the orientation of the leaf at angle Θ_k; and $\hat{r}$ is the direction of the energy flux described by Θ_r, ϕ_r

(i.e., $\hat{r} = (\sin\Theta_r \cos\phi_r, \sin\Theta_r \sin\phi_r, \cos\Theta_r)$) (24)

The elements of CONT_{ijr} represent the weighting coefficients which give the flux contributions from a source layer, j=1,2,3,4,5 , to a sink vegetation canopy layer, i=1,2,3 , from a particular source direction Θ_r, ϕ_r .

These elements for an arbitrary direction, $\hat{r}$, are given in Table 1. $P_o(i,r)$ is the probability of a gap in transversing layer i at direction r . It may approximated by

$$P_o(i,r) \triangleq P_o(i,\Theta_r) = e^{-N(i)\, g(i,\Theta_r) \sec \Theta_r} \qquad (25)$$

where $g(i,\Theta_r)$ is the mean canopy layer projection in direction Θ_r . Mean canopy projection is given by

$$g(i,\Theta_r) = \int_0^{\pi/2} k(\Theta_r,\Theta_k)\, f_{ik}\, d\theta_k \qquad (26)$$

where:

$$k(\Theta_r\Theta_k) \begin{cases} = 2/\pi \cos \Theta_k \cos \Theta_r \ , & \Theta_k \leq \pi/2 - \Theta_r \\ = 4/\pi^2 \cos \Theta_k \cos \Theta_r \ (\phi_k' - \pi/2 - \tan\phi_k') \ , & \Theta_k \geq \pi/2 - \Theta_r \end{cases}$$

$$\phi_k' = \cos^{-1} (-\cot\Theta_k \cot\Theta_r)$$

Program SCALC also calculates the view factor matrix for the canopy. This matrix is used to determine the thermal flux contribution from each vegetation layer and the ground layer which is intercepted by a sensor viewing the canopy at a particular zenith angle. It is given by

$$W(i,\Theta_r) = \underline{VF}(i,\Theta_r) = [VF(1,r)\ VF(2,r)\ VF(3,r)\ VF(4,r)]^T$$

$$VF(1,\Theta_r) = 1 - P_o(1,r)$$

$$VF(2,\Theta_r) = P_o(1,r)[1 - P_o(2,r)]$$

$$VF(3,\Theta_r) = P_o(1,r)\ P_o(2,r)[1 - P_o(3,r)]$$

$$VF(4,\Theta_r) = P_o(1,r)\ P_o(2,r)\ P_o(3,r)$$

Sequence of Required Computer Runs

29. Appendix A contains a listing of all the computer programs utilized in this study. Three of these programs are directly concerned with thermal modeling or preprocessing steps that must be initiated before the thermal calculations may be made. In addition, program SENSIT has been included. This program performs the systematic and repetitive calculations necessary to complete the sensitivity calculations of many of the thermal model parameters.

30. The basic thermal model is program TMODEL. This program assumes that the geometrical characterization of the canopy has been performed and the appropriate $\underline{S}$ matrix, shortwave absorption vector, and view factor matrix have been calculated. The model then performs similar calculations at discrete time intervals, given the specification of the appropriate parameter (emission and absorption characteristics of the canopy elements and the ground, canopy stomatal resistance to water vapor diffusion). Furthermore, the input information must be provided at the discrete time intervals simulated. These data consist of the air temperature, the ground temperature, the wind speed, the relative humidity, and the shortwave flux. The basic philosophy of TMODEL is that for a given type or types of vegetation canopies, one would want to simulate a multitude of scenarios for their thermal behavior based on either ambient meteorological conditions or modifications to the thermal properties of the canopy or understory. Thus, it is usually required to calculate the geometrical characteristics of the canopy type only once and then perform multiple simulations of the canopy with TMODEL.

31. The calculations of the appropriate geometrical flux transfer matrices are done by Program SCALC and Program SRVC for absorption. For both of these programs, detailed canopy geometry information is required.

This includes the leaf area index for each layer, and the leaf slope distribution by layer. In addition, to calculate the shortwave absorption coefficients, average optical properties of the canopy elements are required. The SRVC absorption model is further described in a report by Kimes, Smith, and Ranson (1979).

32. The complete set of geometrical matrices have been calculated for the lodgepole pine canopy in Leadville, Colorado, studies under earlier WES sponsorship, the Douglas-fir canopy from the Cedar River Watershed, near Seattle, Washington, and the oak-hickory deciduous community at the Walker Branch Watershed at Oak Ridge National Laboratory in Tennessee. In addition, the geometrical characterization has been performed for 15 abstract canopies of varying densities and geometrices. These data are given in Appendix B.

33. In summary, given a specific canopy to be studied and for which detailed geometrical measurements have been obtained, Program SCALC and the SRVC absorption model are first used in a preprocessing manner to calculate the appropriate flux-transfer matrices. The data generated from these runs are then used in Program TMODEL. If there is no specific geometrical measurement available for canopies of interest, then one of the 15 theoretical canopies in Appendix B may be appropriate.

34. An example of a complete analysis for the validation experiments is given in Part IV.

PART III: SENSITIVITY ANALYSIS

35. The basic analytic model described in this report may be indicated by the form:

$$\underline{F}(\underline{X},\underline{P},\underline{U}) = 0$$

To simplify notation, $\underline{U}$ will be considered to be an additional set of parameters augmenting the $\underline{P}$ vector, and it will be written that:

$$\underline{F}(\underline{X},\underline{P}) = 0$$

Further, the solution to the system of equations for a specific parameter $\underline{P}_0$ will be indicated as $\underline{X}(\underline{P}_0)$.

36. Sensitivity analysis consists of determining the change in the solution to the model for a small change or perturbation in model parameters, i.e., $X(\underline{P}_0 + \Delta\underline{P})$.

37. The sensitivity function S_{xp} is defined (Tomovic 1963) as:

$$\lim_{\Delta \underline{P}\to 0} \frac{\underline{X}(\underline{P}_0 + \Delta\underline{P}) - \underline{X}(\underline{P}_0)}{\Delta\underline{P}}$$

The sensitivity function may be evaluated analytically by differentiation of the system equations with respect to the parameters under consideration, yielding the following sensitivity equation:

$$\frac{\partial\underline{F}}{\partial\underline{X}}\frac{\partial\underline{X}}{\partial\underline{P}} + \frac{\partial\underline{F}}{\partial\underline{P}} = 0$$

or (27)

$$\underline{S}_{xp}\frac{\partial\underline{F}}{\partial\underline{X}} + \frac{\partial\underline{F}}{\partial\underline{P}} = 0$$

Alternatively, computer simulations may be employed in which the parameters are systematically and separately perturbed from nominal values and new canopy temperatures are determined.

38. As indicated in Part I, this latter approach was employed for this study. Program SENSIT was written to facilitate the calculation (Appendix A).

39. Program SENSIT requires environmental data and temperatures for each layer to initialize the analysis. In addition, geometrical factor matrices describing a particular canopy are required. The environmental data used was collected by WES personnel at Zweibrücken Air Force Base in West Germany on 4 October 1979. Data was selected at 0600 hours and 1100 hours to provide for nighttime (predawn) and daytime analysis. Initial state temperatures for each layer were determined from simulation results. The sensitivity analysis was performed for both the Douglas-fir and oak-hickory canopies resulting in a total of four analyses. Table 2 lists the initial environmental parameters and initial temperatures for each sensitivity run. Graphical results of parameter changes versus predicted temperatures are found in Appendix C.

40. The daytime sensitivity analysis showed that the predicted canopy temperatures were most sensitive to the air temperature within the canopy. A 10 percent change in canopy air temperature resulted in nearly a 10 percent change in all layers for both types of canopies. Decreasing longwave absorption coefficients by 10 percent resulted in less than a 0.5°C change in predicted temperatures and showed a layer by layer dependence for both canopies and time periods. Predicted canopy temperatures showed minimal sensitivity to changes in air and ground temperatures as input to the model. Temperature predictions were nearly equally sensitive to the shortwave absorption in all three layers

for both canopies. Changing the canopy emissivity in the top layer for both canopies had little effect on predicted temperature for layer 1, but slightly increased sensitivity was noted for the two lower canopy layers. Decreasing ground emissivity from 1.0 to 0.9 increased predicted temperatures by less than 0.5°C. Changing relative humidity showed little effect on canopy temperatures with the daytime oak-hickory analysis exhibiting the greatest sensitivity. A linear relationship was noted between predicted canopy temperatures and the parameters discussed above. Only stomatal resistance and wind speed analyses showed nonlinear trends. Sensitivity plots of stomatal resistance for Douglas-fir and oak-hickory are shown in Figure 2. In both cases the plots are nonlinear above R_l values of 0.08 min/cm. Other analyses not reported here showed a linear relationship for R_l greater than 0.08 min/cm to about 1.5 min/cm. Figure 3 shows plots of wind speed versus predicted temperature for Doulgas-fir daytime and nighttime analyses. The daytime plot shows an increase in temperature with decreasing wind speed; but at night, temperatures decrease slightly with decreasing wind speed.

PART IV: MODEL VALIDATION EXPERIMENTS

41. As discussed earlier, the objective of the field experiments was to provide data sets from diverse targets and environmental conditions for validation of the Colorado State University (CSU) thermal canopy model. Two existing research sites were located through the efforts of WES personnel that proved to be ideal for the experiments. The Cedar River site was located in a Douglas-fir forest near Seattle, Washington. A second research site, the Walker Branch Watershed, was typical of an Appalachian deciduous forest and was located near Oak Ridge, Tennessee. Both research sites were being used for ongoing research in forest meteorology and possessed extensive instrumentation and computerized data acquisition support. The principal scientist responsible for the development of the Cedar River site was Dr. Leo J. Fritschen of the College of Forest Resources, University of Washington, while Dr. Boyd A. Hutchison of the Atmospheric Turbulence and Diffusion Laboratory (ATDL), National Oceanic and Atmospheric Administration (NOAA) was responsible for the Walker Branch site. Further descriptions of these sites are given below.

Experimental Design

42. The model validation experiments were designed by CSU and WES personnel with cooperation from Drs. Fritschen and Hutchison. The goal was to provide appropriate input and validation data for the CSU canopy models. Input data included optical, thermal, and environmental parameters for two consecutive 24-hour periods of the targets. Validation

data consisted of foliage temperatures. In addition, thermal scanner imagery was to be obtained by local National Guard units at specified times throughout the measurement periods. Characterization of the foliage angle distributions of the canopies was also required. Input data requirements and methods are discussed in a later section.

43. WES personnel were responsible for overall mission coordination, thermal radiometric measurements of ground and canopy, air temperature measurements in the lower 1.5 m of the canopies, and arranging for National Guard thermal scanner overflights of the experimental sites. CSU personnel communicated requirements for micrometeorological data to Drs. Fritschen and Hutchison, obtained foliage geometry data from the sites, and performed necessary optical measurements required to run the canopy models. Groups headed by Drs. Fritschen and Hutchison provided site access, operated and maintained the data acquisition systems, and provided assistance for interpreting the micrometeorological data. In addition, Dr. L. W. Gay of the School of Renewable Natural Resources, Arizona University at Tucson participated in the Cedar River Douglas-fir experiment to test the use of direct beam depletion measurements for determining forest biomass.

Site Descriptions

44. Two established research sites were available for this study. A site near Seattle, Washington, developed and maintained by Dr. Leo Fritschen of the University of Washington, provided data for a stand of mature Douglas-fir. Dr. Boyd Hutchison of ATDL/NOAA made available an oak-hickory site near Oak Ridge, Tennessee and provided necessary

environmental data. A detailed description of these sites is provided below.

Cedar River, Washington

45. The Cedar River, Washington, study site is located on the A. E. Thompson Research Center at the western end of the Cedar River Watershed. The site lies in the Puget Sound Basin at the western foot of the Cascade Mountains 55 km southeast of Seattle, Washington, at 47°23'N and 121° 56'W. The elevation is approximately 215 m above mean sea level.

46. The area was logged prior to 1924 and subsequent fires resulted in a mosaic of different aged stands (Jensen, 1976). The most common community on the site is Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco). This naturally regenerated stand was approximately 41 years old with an average tree spacing of 5.8m. There were 572 trees per hectare consisting mainly of Douglas-fir, a few hemlock, and maple (Figure 4). Ground cover consisted of fern, salal, huckleberry mosses, and litter (Figure 5). Bare soil areas were minimal and occurred only on roads and other localized disturbed areas. Soil at the site consisted of Barneston gravelly, loamy sand originating from glacial outwash.

47. The specific study site was located at a micrometeorological observatory maintained and operated by the University of Washington. Average height of the Douglas-fir stand was about 28 m with an average LAI of approximately 7.8. Located at this site was a 28-m-tall Douglas-fir tree contained in a lysimeter (Fritschen, Cox, and Kinerson, 1973). The site adjacent to this tree was instrumented to provide data for

evapotranspiration studies. These data included wet and dry bulb temperatures, soil temperatures, global shortwave radiation, precipitation, and wind speed and direction. In addition, needle surface temperatures were monitored at several points around the lysimeter tree near the top and center of the canopy. These data were recorded at selected time intervals by a computerized data acquisition system. A 33-m walk-up tower was available adjacent to the lysimeter tree to provide access to needle temperature sensors and other measurement devices.

Walker Branch, Tennessee

48. The Walker Branch study site is located near the Walker Branch Watershed research facility on the U.S. Department of Energy Reservation near Oak Ridge, Tennessee, at $35^{o}58'$N and $84^{o}15'$W. An intensive forest meteorological research site operated by the ATDL of the NOAA was made available for this study. This research area is situated on a ridge top about 70 m above the valley floor at an elevation of 335 m above mean sea level.

49. The area is representative of an Appalachian deciduous forest (Hutchison, 1977). The species composition of the stand is dominated by various species of oak and hickory, including *Quercus alba*, *Quercus prinus*, *Quercus velutina*, *Carya glabra* and *Carya ovata*. *Acer rubra* (red maple), *Prunus serotina* (black cherry), *Liriodendron tulipifera* (yellow popular) are less frequently found. Common understory plants include *Oxydendron arboreum* (sour wood), *Cornus florida* (flowering dogwood) and *Cercis canadensis* (eastern redbud). The average height of the

codominant trees forming the canopy is about 21.5 m with lower limit of the live crown being 15 m above the ground. These heights vary greatly due to the uneven age of the stand (Figure 6). Basal area was approximately 26 m^2 ha^{-1}. The site appeared parklike due to a fire that occurred several years ago. Understory growth, however, is abundant. The ground is covered by an accumulation of litter (Figure 7) with bare soil occurring only in disturbed areas. In addition, fragmented, grey-colored rock covered the road surfaces. A metal track was in place beneath the stand to provide all-weather access for research vehicles. This track was covered with litter by ATDL personnel during the field experiments.

50. The site is extensively instrumented to record data pertinent to forest meteorology research as well as the thermal modeling studies. Hutchison (1977) gives a detailed description of the research facility.

Modeling Input Data

51. The data collected at the two sites included foliage and background optical parameters, geometry characterization measurements, and environmental measurements. This section describes the data required for the models and the techniques or sources used to acquire it. Listings of the data values are included in Appendix D.

Foliage geometry

52. The structure of a canopy defined by the foliage inclination angles and LAI is important for characterizing the interactions of radiation with the canopy. These inputs are required by the optical SRVC

model (Oliver and Smith 1974) to estimate the shortwave absorption of a canopy and by the thermal model to describe longwave energy exchanges inside and outside of the canopy.

53. The procedure for determining foliage geometry included acquiring high-contrast black-and-white slide photography of canopy silhouettes. These slides serve as input to a laser diffractometer which characterizes the frequency of occurrence of foliage angles in terms of the resulting diffraction pattern. The diffraction patterns are optically sampled, and the results are analyzed with a series of computer programs. See Kimes, Smith, and Ranson (1979) for a discussion of the theory and procedures.

54. The walk-up towers at both sites provided an excellent platform for acquiring slides of the canopies. For the purposes of the modeling, the canopies were partitioned into three layers of equal height. Photographs were taken for each layer from several directions from the tower. This provided a larger sample size and minimized effects of azimuthal asymmetry. Ideally, the photographs should be taken with a white backdrop placed behind the target to eliminate background trees and shadows. However, this was impractical for the canopies under study. As a result, the slides were manually interpreted to delineate branches of the desired tree in the photographs. This was done by projecting the slide on white paper and tracing the appropriate branches. Earlier work by Kimes, Smith, and Ranson (1979) showed that for complex canopies, such as conifers, two interpretations are required: one with all branches represented, and a separate tracing including only branches bearing foliage. High-contrast slides of these tracings were used as input to the laser diffractometer. The branch and foliage measurements were

combined later to provide the inclination angle distributions for each layer.

55. The calculated foliage angle distributions for a Douglas-fir canopy are shown in Figure 8. For comparison purposes, distributions of lodgepole pine (Pinus contorta) reported by Kimes, Ranson, Kirchner, and Smith (1978) are included. Figure 9 shows foliage angle distributions for oak-hickory. These data were derived from direct measurements provided by Dr. Hutchison. Laser diffraction results for oak-hickory were unavailable due to equipment problems. For comparison a one-layer distribution for Russian olive (Elaeagnus angustifolia) reported by Kimes, Smith, and Ranson (1979) is included.

Leaf area index

56. LAI is defined as the total one-sided leaf area occupying the horizontally projected area of the canopy. For example, an LAI of 5 indicates that five layers of leaves could be overlayed to completely fill an area equal to the canopy projection on the ground. LAI's for this study were determined from data provided by Drs. Fritschen and Hutchison. LAI's for the Douglas-fir canopy were derived from measurements reported by Kinerson and Fritschen (1971). In this report, graphs of canopy height $z(m)$ versus surface area density $F(z)$ ($m^2\ m^{-3}$) for nine sample plots are given. Integrating $F(z)$ over height gives the needle surface area index NSAI for a particular height increment dz. Data points were taken from the graphs and averaged for given heights to produce a single average surface density curve. This curve was partitioned into three layers of equal height and layer NSAI's determined

by Simpsons Rule (Figure 10). For our modeling purposes, LAI values were determined by dividing NSAI for each layer by two.

57. LAI for the oak-hickory canopy was determined from data provided by ATDL. These data consisted of a graph of cumulative LAI versus height and graph of LAI at given heights through the canopy. A smoothed version of the latter is presented as Figure 11.

Canopy density parameter

58. This parameter ranges from 0 to 1 and describes the spatial dispersion of foliage elements within a canopy. As values approach 1, gaps in the canopy are less frequent since the foliage is more regularly dispersed. This parameter is used in the equation to determine the probability of gaps occurring in a canopy layer. A value of 0.1 was chosen for all model runs. For a detailed discussion of spatial dispersion of canopies see deWit (1965).

Canopy optical parameters

59. The shortwave transmission and reflectance of foliage elements are required as inputs for estimating average absorption coefficients as discussed below. Canopy element transmission values were measured at the study sites, but reflectance values were derived from the published literature.

60. The procedure for determining transmission consisted of placing a needle or leaf over a narrow slit on a flat plate attached to a photodiode and recording a reading of the amount of light passing through the sample. Measurements were made in four wavelength bands--at 4.8μm, 0.55μm, 0.68μm, and 0.80μm. The transmission measurements were then

ratioed to the incoming spectral irradiance measured from a $BaSo_4$ standard reflectance panel. The measurement procedure was repeated for several foliage samples and the results averaged. Natural illumination was used for the Douglas-fir needles; however, because of rapidly changing irradiance conditions at the Walker Branch site, a bank of fluorescent tubes was used as the irradiance source. The transmission measurements were integrated over wavelength to estimate the average shortwave transmittance from 0.48 to 0.80μm. This wavelength interval was assumed adequate.

61. Shortwave reflectance values for Douglas-fir were obtained from data presented by Jarvis, James, and Landsberg (1976). Curves for old and new Douglas-fir needles were digitized and averaged. The resulting curve was then integrated over the wavelength interval from 0.45μm to 1.2μm to obtain the average shortwave reflectance coefficient. The oak-hickory canopy element reflectance was determined from data presented by Colwell (1969). Data for maple, oak, and yellow poplar were averaged and integrated over the wavelength interval 0.45μm to 1.2μm.

62. In addition to foliage transmission and reflectance estimates, an average background reflectance was determined at both sites. Measurements were made of various surface covers such as litter, bare soil, and ground cover vegetation. The results were weighted according to visual estimates of occurrence and then averaged and integrated.

Shortwave absorption coefficients

63. The absorption of global shortwave radiation by canopy layers is an important component in the daytime energy budget. It is, however, difficult to directly measure and must be estimated with models. These

coefficients were approximated with the SRVC model modified for absorption (Kimes, Smith, and Berry, 1980). The procedure involved running model simulations with appropriate canopy layer geometry, LAI, and optical parameters for an average zenith sun angle of 45°. The resulting absorption values represent the proportion of shortwave absorption in each canopy layer. Since the thermal model requires absorption per unit leaf area, the simulated absorption coefficients were divided by the one-sided leaf area in a given layer.

Stomatal resistance

64. The resistance of the leaf to water vapor diffusion depends on many environmental factors. Leaf stomates open and close in response to microclimatic and soil conditions and regulate the cooling of the plant through evapotranspiration. Thus, stomatal resistance is important when considering energy budget analysis of plants. This parameter is difficult to measure, so for modeling purposes average values were used as constants. The value for Douglas-fir was set at 0.66 min/cm as an average value for coniferous forest (Kimes, Smith, and Ranson, 1979). Stomatal resistances were determined from data provided by Hutchison*. These data ranged from 0.04 to 0.07 min/cm for sun leaves. The upper value was selected for use in all deciduous canopy simulations.

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* Personal communication; B. A. Hutchison, Atmospheric Turbulence and Diffusion Laboratory, National Oceanic and Atmospheric Administration, Oak Ridge, Tennessee, 1979.

Emissivity and absorptivity

65. The ability of a canopy element to emit and absorb longwave radiation is expressed by the emissivity and absorptivity coefficients specified for each component in the canopy layers and for the ground layer. Available literature values or direct measurements could, consequently, be substituted. For all of the analyses reported here, the emissivity ε_i and absorptivity α_i are set equal to 1.0 for each of the three canopy layers. Emissivity of the ground ε_g was also set at 1.0. Emissivity of the air ε_a was calculated as a function of air temperature by the following function (Hudson, 1969):

$$\varepsilon_a = 1.0 - 0.0261\ e^{(-0.000777\ T_a^{\ 2})}$$

Canopy Temperature Measurements

66. Since the purpose of the experiments was to collect data sets for validation of the thermal model, actual canopy foliage temperature measurements were required. The experiments were designed to provide measured canopy temperatures, as well as thermal scanner images of the sites.

67. The experimental setup at the Cedar River site included temperature measurements for a number of individual Douglas-fir needles. The temperature sensors were located around the lysimeter tree at average heights of 26 m and 20 m. The measurements at a given height were averaged to give an average layer measurement. The 26-m measurement was assumed to represent the average canopy temperature for layer 1. The 20-m measurement approximated layer 2, although its location was closer to the boundary between layer 1 and layer 2. These layer temperatures are plotted along with air temperature against time in Figure 12.

68. No individual leaf temperature measurements were available at the Walker Branch site, so a portable thermal radiometer* was used to monitor the canopy temperature throughout a 24-hour period. The procedure was to position the instrument upward from the ground at the canopy and slowly move it until the maximum temperature was recorded. This was done to minimize errors due to the presence of sky or clouds in the field of view. Figure 13 shows a plot of the canopy temperature with air temperature above the canopy and ground temperature against time.

69. In addition to the geometrical, optical, and thermal parameters discussed above, a set of dynamic variables characterizing the microclimate of the target is required to drive the thermal model. These parameters consist of air temperature above the canopy, ground surface temperature, wind speed at the top of the canopy, relative humidity, and global shortwave radiation.

70. Air temperature, ground temperature, and shortwave radiation are important components for energy exchange into and within the system; whereas wind speed and relative humidity are important for determining forced convection loss and evapotranspirative cooling of plants, respectively.

71. Environmental data were provided from the automated recording systems at the two sites. Air and ground temperatures and global shortwave radiation were measured directly. Relative humidity was determined from wet and dry bulb temperatures. All measurements were

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* Barnes Insta-Therm, Barnes Engineering Corporation.

either instantaneous or short time interval averages. Plots of the four environmental parameters are shown in Figure 14 for Cedar River and Figure 15 for Walker Branch.

Model Validation Results

72. The data collected for the coniferous Doulgas-fir and deciduous oak-hickory canopies provided a good means of testing the thermal model under these diverse conditions. Three-layer canopy temperature simulations were made over a 48-hour period with both data sets and the results were compared with measured temperatures.

Douglas-fir canopy

73. The thermal model was run with environmental data acquired over the 48-hour period of 4-5 August 1979. These data plus the required geometrical factor matrices which include the longwave exchange coefficients, the sensor view angle weighting factors, and average shortwave absorption coefficients are listed in Appendix D. The emissivities and thermal absorption coefficients for each layer were set to 1.0. The total canopy resistance to water vapor diffusion was input at 0.66 min/cm.

74. A plot of the simulated three-layer temperatures with measured air temperature is shown in Figure 16. The layer 1 simulated temperatures follow the trend of air temperature, but fall below during the night and are higher during the day. The layer 2 and layer 3 predictions are nearly equal to air temperature throughout the 48-hour period. Comparisons of measured and predicted needle temperatures for layers 1 and 2 are presented as Figures 17 and 18, respectively.

75. The layer 1 predicted temperatures vary from the measured temperature by a maximum of $3^{o}C$. These deviations were observed during the daytime hours under very hazy skies. Nighttime predictions deviated from measured by $2^{o}C$ or less with the maximum deviations occurring under conditions of fog. This leads to the conclusion that the thermal model may be most valid for days with primarily direct solar radiation and clear nights where radiative cooling is occurring.

Oak-hickory canopy

76. Environmental data acquired at the Walker Branch site for the 48-hour period from 18-19 August 1979 were used to validate the thermal model for a deciduous oak-hickory canopy. Emissivities and thermal absorption coefficients for the three canopy layers were set to 1.0. Canopy resistance to water vapor diffusion was input as 0.07 min/cm and held constant. The input environmental and geometrical factor data for this canopy simulation are presented in Appendix D.

77. Figure 19 presents the three-layer canopy temperature predictions along with measured air temperature. Nighttime simulations were nearly equal to air temperature, but daytime predictions varied by a maximum of $2^{o}C$ over air temperature.

78. Measured temperatures were compared to predicted results for layer 2 and are shown in Figure 20. The agreement between model and measured temperatures was quite good. The largest deviation ($3^{o}C$) occurred in the afternoon; but morning and nighttime predictions varied by only $1^{o}C$ or less.

Summary

79. The results of the model validation study indicate that the thermal canopy temperature model provided good estimates of actual temperatures for nighttime periods to within 2°C for both canopies studied. Daytime simulations generally underestimated measured temperatures for Douglas-fir and overestimated temperatures for oak-hickory. The results indicate that the model may not adequately account for energy transfers under foggy or very hazy conditions.

PART V: RECOMMENDATIONS

80. Two broad directions for further research and development are suggested in the paragraphs below. The first set of tasks represent logical extensions or improvements to the thermal model utilized in this study. Also, a not-quite-so-obvious extension to the calculation of the geometrically dependent flux transfer matrices is outlined. The second thrust recommended for further development is concerned with parameter estimation techniques which can be used to estimate model parameters, control (or input) variables, and elements of the state vector itself. Two techniques are described. The first technique based on sensitivity functions is appropriate for the steady-state version of the model. The second method, based on the Kalman filter, is more appropriate for dynamic representation of the thermal model.

Model Improvements

81. The most urgent need for model improvement is to evaluate different theories for the height dependence of air temperature within the canopy and of the vertical profile for wind speed. It is particularly appropriate to examine those techniques which would yield these temperature and wind profiles from a few limited measurements. The structure of the current thermal model can easily include vertical variations in the two parameters; they are held constant for the want of better knowledge and for simplicity.

82. The utility of the model could be extended if a ground temperature module was included. Particularly for this extension it may be appropriate to develop a time-dependent version of the model to include heat storage effects.

83. A useful exercise, but of lesser priority, would be to systematically examine the alternative formulations expressed by various authors for different components of the energy budget equation; that is, evapotranspiration, sensible heat, and so forth. There is no clear rationale for selecting one expression over another. However, the separate expressions can be programmed and sensitivity analysis performed on the individual expressions.

84. Finally, further analysis of the structure of the geometrical matrices should be carried out to determine if either an analytical decomposition of the matrices into a leaf density (leaf area index) component and leaf slope distributions can be constructed. If an analytical decomposition is not possible, then numerical interpolation techniques should be investigated.

85. As an example, consider the expressions for the view factor matrix $\underline{VF}(i,\Theta)$ where Θ_r is the zenith view angle and $i=1,2,3,4$ corresponds to contributions from the three vegetation layers and the ground surface:

$$\underline{VF}(i,\Theta_r) = [VF(1,r)\ VF(2,r)\ VF(3,r)\ VF(4,r)]^T$$

$$VF(1,\Theta_r) = 1 - P_o(1,r)$$

$$VF(2,\Theta_r) = P_o(1,r)\ (1 - P_o(2,r)$$

$$VF(3,\Theta_r) = P_o(1,r)\ P_o(2,r)\ (1 - P_o(3,r))$$

$$VF(4,\Theta_r) = P_o(1,r)\ P_o(2,r)\ P_o(3,r)$$

where:

$P_o(i,\Theta) = e^{-LAI\ g(i,\Theta)\ \sec\Theta}$

LAI (i) = the mean leaf area index for layer i

$g(i,\Theta)$ = the mean canopy projection of vegetation layer i in the direction Θ, depending only on the leaf slope distributions for layer i

86. A direct factorization is not apparent. However, particularly for large LAI a Taylor series expansion would yield a more tractable form. Alternately, LAI could be varied between 0 and 10 and numerical tables generated.

Parameter Estimation

87. Two different approaches are suggested for estimation of parameters, control vector inputs, and/or selected components of the unknown state vector, that is the average canopy temperature for the three different layers. One approach is more applicable to the steady-state conditions; the second approach is more appropriate for the time-dependent version of the model. In each case it is assumed that selected measurements of canopy temperatures are available for some time periods and that some of the parameters and control vector components are also known. A typical scenario would be that the top layer canopy temperature is measured over a diurnal cycle and that all parameters and input components are known except for the $\underline{S}$ matrix, the longwave flux transfer matrix. It is then desired to estimate the $\underline{S}$ matrix which depends on the geometrical properties of the canopy and evaluate the fit on a second diurnal cycle. Other scenario examples can be envisioned. In this section, general development of the two-parameter estimation techniques are indicated.

88. First, consider the steady-state situation where the model is given by the following equation:

$$\underline{F}(\underline{X},\underline{P},\underline{U}) = 0$$

where the symbols have the same meaning as given earlier. For this situation the parameter estimation technique of nonlinear systems as described by Durando and Leondes (1976) is recommended. For simplicitity

the $\underline{U}$ vector is appended to the $\underline{P}$ vector and the equation is re-expressed as:

$$\underline{F}(\underline{X},\underline{P}) = 0$$

Further, it is assumed that observation variables are the canopy temperature variable, x , directly. Given a known measurement, $\underline{X}_0\underline{F}(\underline{X},\underline{P})$ becomes a function of $\underline{P}$ only. Assume an initial estimate of $\underline{P},\underline{P}_0$. Then $\underline{F}(\underline{X},\underline{P})$ can be expanded about P_0 :

$$\underline{F}(\underline{X},\underline{P}) - \underline{F}(\underline{X}_0,\underline{P}_0) = \frac{\partial \underline{F}}{\partial \underline{P}}_{\underline{P}=\underline{P}_0} (\underline{P} - \underline{P}_0) + \underline{\varepsilon} \tag{28}$$

For the steady-state formulation $\underline{F}(\underline{X},\underline{P}) = 0$; ε is the error vector. Iteration is continued until convergence, i.e.,

$$\underline{P}_{n+1} = \underline{P}_n + \delta\underline{P} \tag{29}$$

89. If observations are available for more than one time interval, the optimal $\underline{P}$ is chosen which minimizes the sum of $\varepsilon^T\varepsilon$ over all time intervals. More general formulations of this approach, including the use of a variable increment step size, are given in the paper by Durando and Leondes.

90. The second technique proposed is applicable to the time-dependent formulation of the thermal model given:

$$M \frac{\partial \underline{X}}{\partial T} = \underline{F}(\underline{X},\underline{P},\underline{U},T) \tag{30}$$

where:

M = specific heat capacity of the system

T = time

The general approach recommended here is the use of the Kalman filter after first linearizing the system. Specifically,

$$\underline{X} = \underline{A}\ \underline{X} + \underline{B}\ \underline{U} + \underline{W} \tag{31}$$

$$\underline{Z} = \underline{H}\ \underline{X} + \underline{V} \tag{32}$$

where $\underline{X} = \partial\underline{X}/\partial T$ represents the dynamical equations of the system, A and B are expansion matrices, and $\underline{W}$ represents the modeling error.

91. $\underline{Z}$ is the observation vector, which now permits transformation on the state vector (canopy temperature), and $\underline{V}$ is the observation noise.

92. Kalman filtering on the state vector or on the augmented state vector, that is, after appending $\underline{P}$ or $\underline{U}$ to $\underline{X}$, is then given by the standard expressions (Friedland 1972):

$$\hat{X}_n = \tilde{X}_n + K_n\ (Z_n - H\ \tilde{X}_n) \tag{33}$$

$$\tilde{X}_n = \Phi_{n-1}\ \hat{X}_{n-1} \tag{34}$$

where:

$$K_n = \tilde{P}_n\ H_n^T\ (H_n\ \tilde{P}_n\ H_n^T + V_n)^{-1} \tag{35}$$

$$\tilde{P}_n = \Phi_{n-1}\ \hat{P}_{n-1}\ {}^{T}_{n-1} + B_{n-1}\ W_n\ B^T_{n-1} \tag{36}$$

$$\hat{P}_n = (I - K_n\ H_n)\ \tilde{P}_n \tag{37}$$

Φ is the transition matrix for the system, n represents the discrete time interval, and $\tilde{X}$ describes the model predictions.

93. An additional $\hat{\underline{X}}_o, \hat{\underline{P}}_o$ is required if many time intervals are available, e.g., a diurnal cycle; however, the final estimates are insensitive to these values.

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Table 1

Expressions for contribution coefficients $CONT_{ij\ell}$ for sink layer i, source component j, and leaf slope index r; $P_o(i,r)$ = probability of gap for layer i and leaf slope index ℓ.

Source Layer	Sink Layer 1	Sink Layer 2	Sink Layer 3
1	$P_o^{1/2}(1,r)$	$P_o(1,r)\ P_o^{1/2}(2,r)$	$P_o(1,r)\ P_o(2,r)\ P_o^{1/2}(3,r)$
2	$2(1-P_o^{1/2}(1,r))$	$P_o^{1/2}(2,r) - P_o^{1/2}(2,r)\ P_o(1,r)$	$P_o^{1/2}(3,r)\ P_o(2,r) - P_o^{1/2}(3,r)\ P_o(2,r)\ P_o(1,r)$
3	$P_o^{1/2}(1,r) - P_o^{1/2}(1,r)\ P_o(2,r)$	$2(1 - P_o^{1/2}(2,r))$	$P_o^{1/2}(3,r) - P_o^{1/2}(3,r)\ P_o(2,r)$
4	$P_o^{1/2}(1,r)\ P_o(2,r) - P_o^{1/2}(1,r)\ P_o(2,r)\ P_o(3,r)$	$P_o^{1/2}(2,r) - P_o^{1/2}(2,r)\ P_o(3,r)$	$2(1 - P_o^{1/2}(3,r))$
5	$P_o^{1/2}(1,r)\ P_o(2,r)\ P_o(3,r)$	$P_o^{1/2}(2,r)\ P_o(3,r)$	$P_o^{1/2}(3,r)$

Table 2

Initial environmental and initial temperature data used for sensitivity analyses for the Douglas-fir and oak-hickory canopies

Environmental Data

Time hours	A_T °C	G_T °C	WS cm/s	RH	SWR w/m^2
0600	10.6	10.7	136.0	0.72	0.0
1100	18.2	19.0	110.0	0.84	299.7

Initial Temperatures, °C

	Time hours	Layer 1	Layer 2	Layer 3
Douglas-fir	0600	9.0	10.1	10.1
	1100	18.4	18.2	18.2
Oak-hickory	0600	10.1	10.5	10.5
	1100	18.8	18.5	18.2

SINK VARIABLE		SOURCE VARIABLE
	SKY	J=1
I-1	VEGETATION LAYER ONE	J=2
I=2	VEGETATION LAYER TWO	J=3
I=3	VEGETATION LAYER THREE	J=4
	GROUND LAYER	J=5

Figure 1. Diagram showing sink and source variable indices used in in the model energy flow formulations

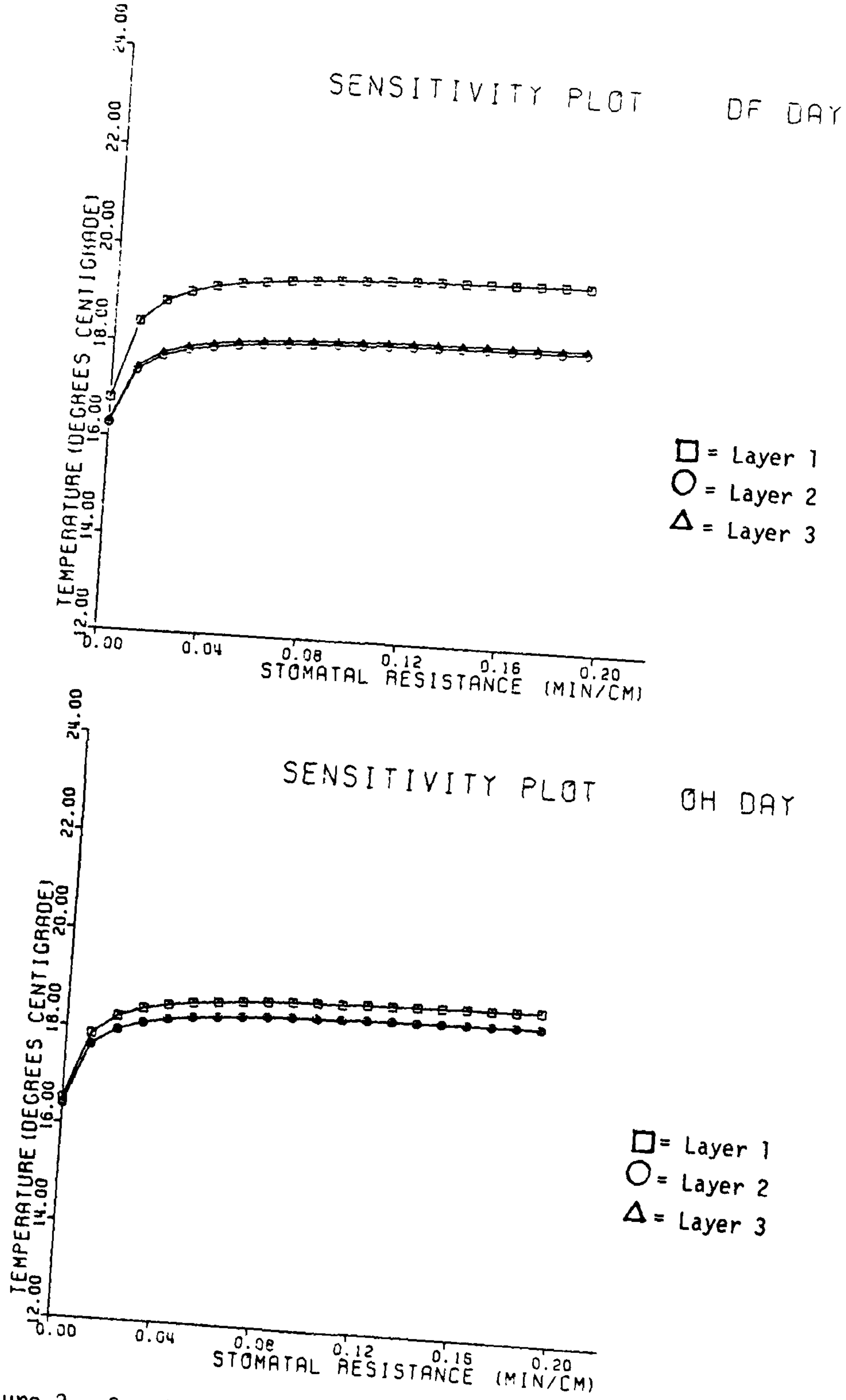


Figure 2. Sensitivity plots of stomatal resistance versus predicted canopy temperature for Douglas-fir (top) and Oak-hickory daytime analyses

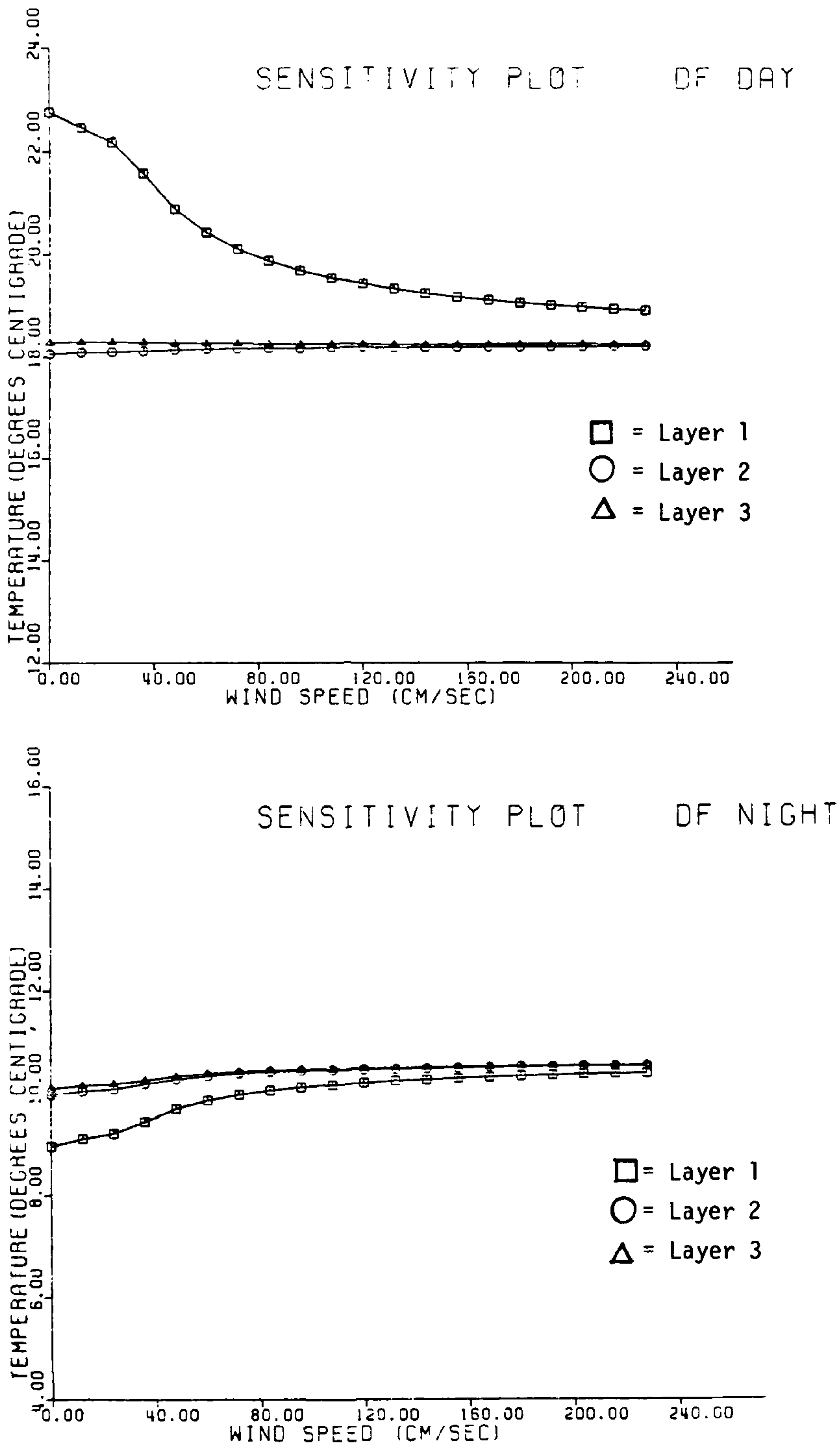


Figure 3. Sensitivity plots of wind speed versus predicted canopy temperature for Douglas-fir day and nighttime analyses

Figure 4. Aerial view of the Douglas-fir canopy at Cedar River, Washington, site; object in center of photograph is a greenhouse enclosure over the lysimeter tree; structure not in place at the time of the experiments (photo courtesy of Leo J. Fritschen)

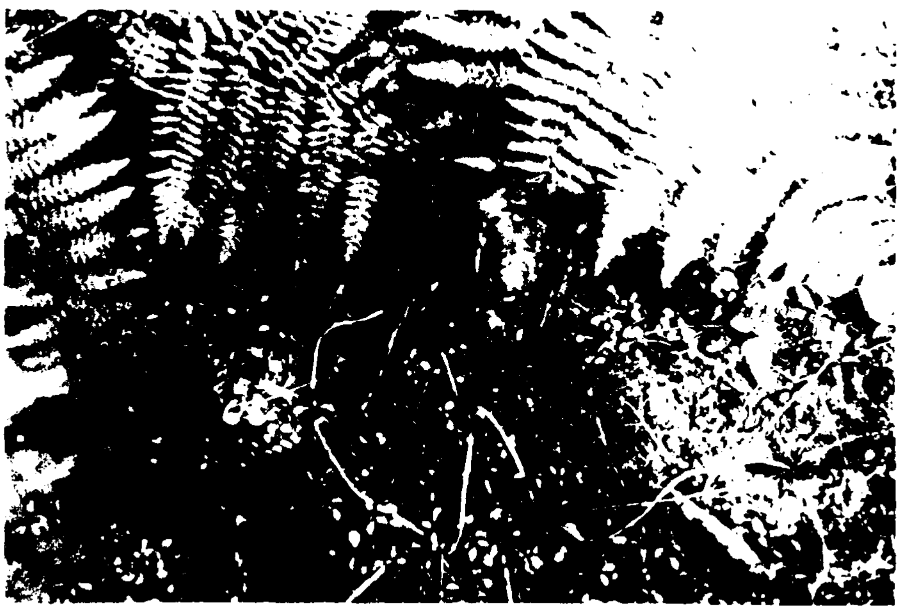


Figure 5. Typical ground cover at the Cedar River site

Figure 6. Oblique view of deciduous canopy at Walker Branch site showing height variations of tree crowns

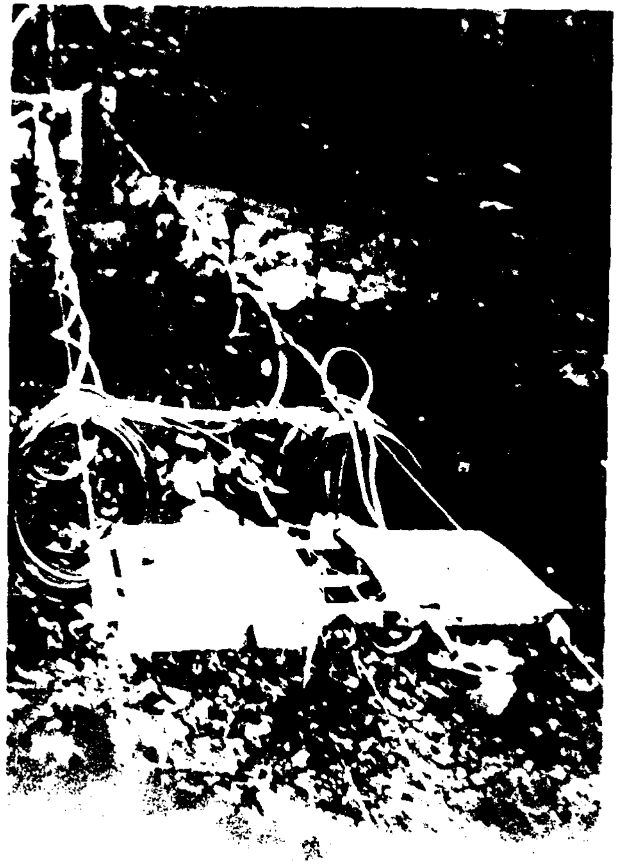
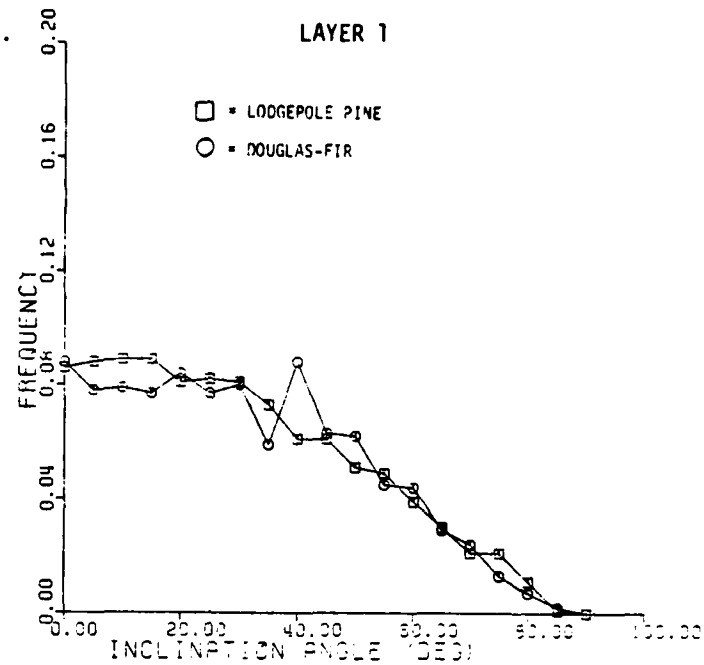


Figure 7. Ground cover at Walker Branch site consisting primarily of litter and seedling trees; the cart (center) is mounted on a tram system and measured shortwave and photosynthetically active radiation at bottom of canopy

A.



B.

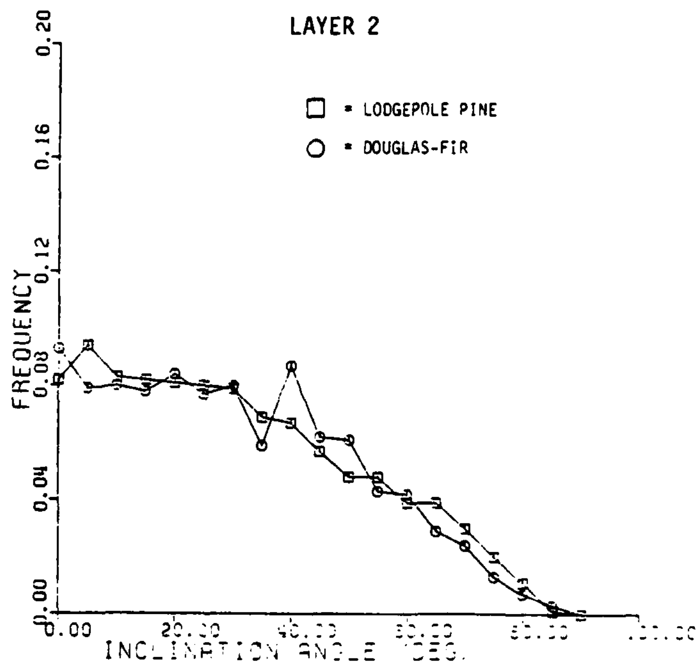


Figure 8. Comparative plots of foilage angle frequency for Douglas-fir and lodgepole pine. A) Layer 1, B) Layer 2 and C) Layer 3 (Continued)

C.

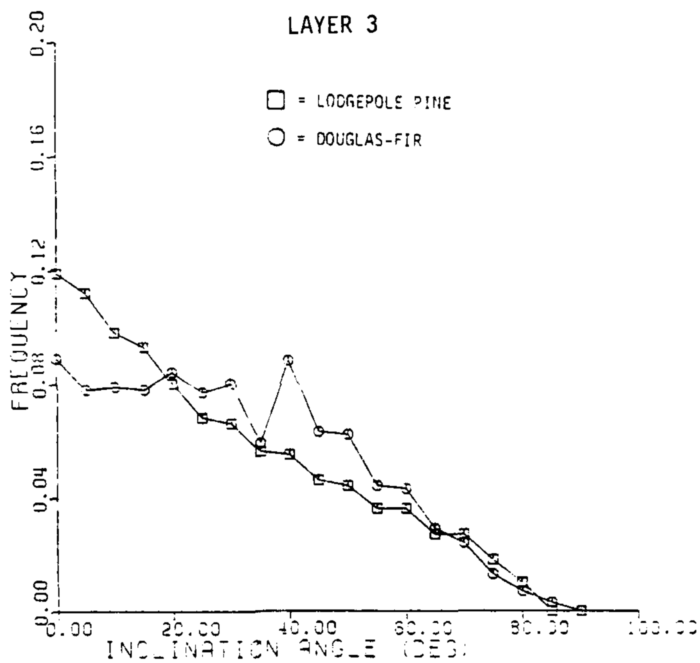


Figure 8. Concluded.

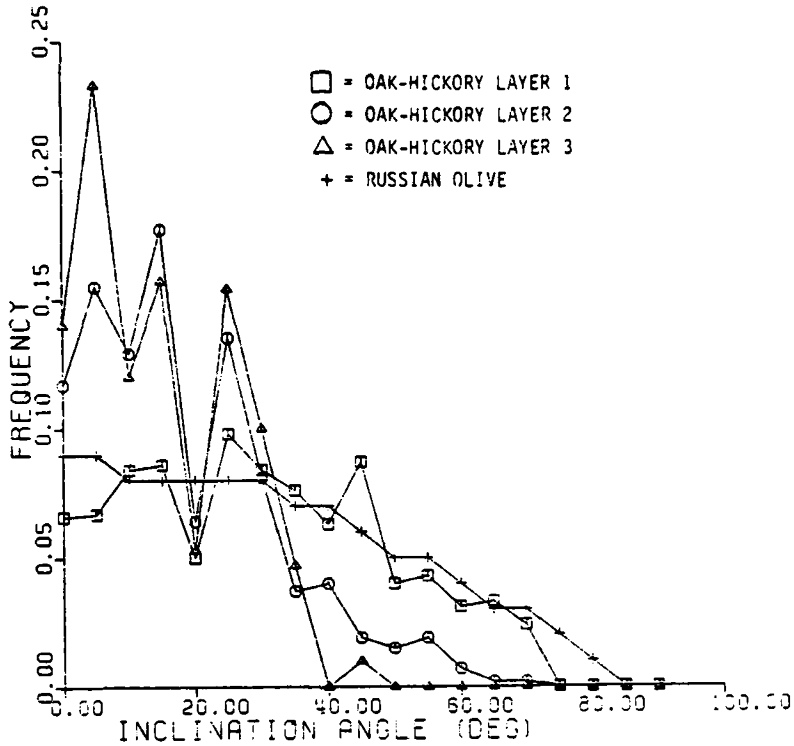


Figure 9. Foilage inclination angle frequency plots for the three layer oak-hickory canopy and a one-layer Russian olive canopy.

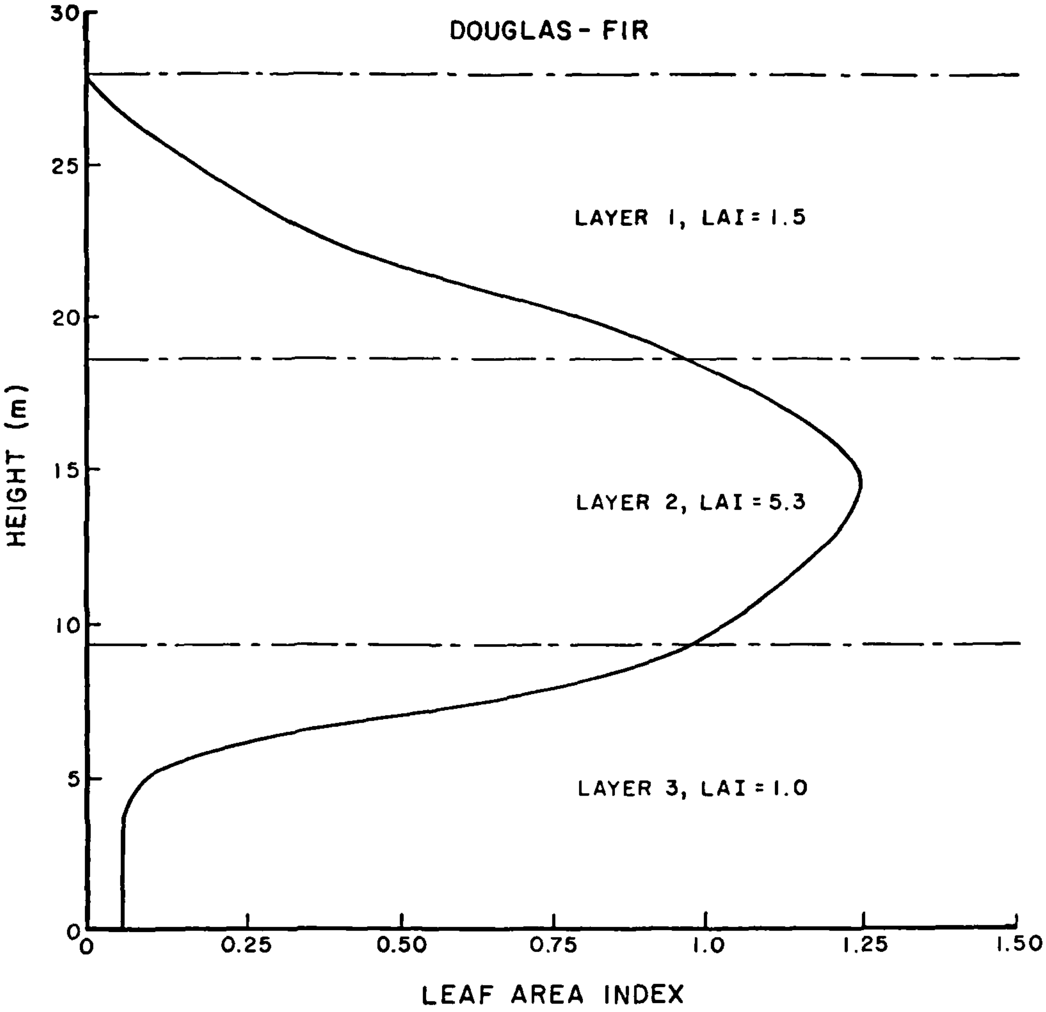


Figure 10. Leaf area index distribution for the Douglas-fir canopy

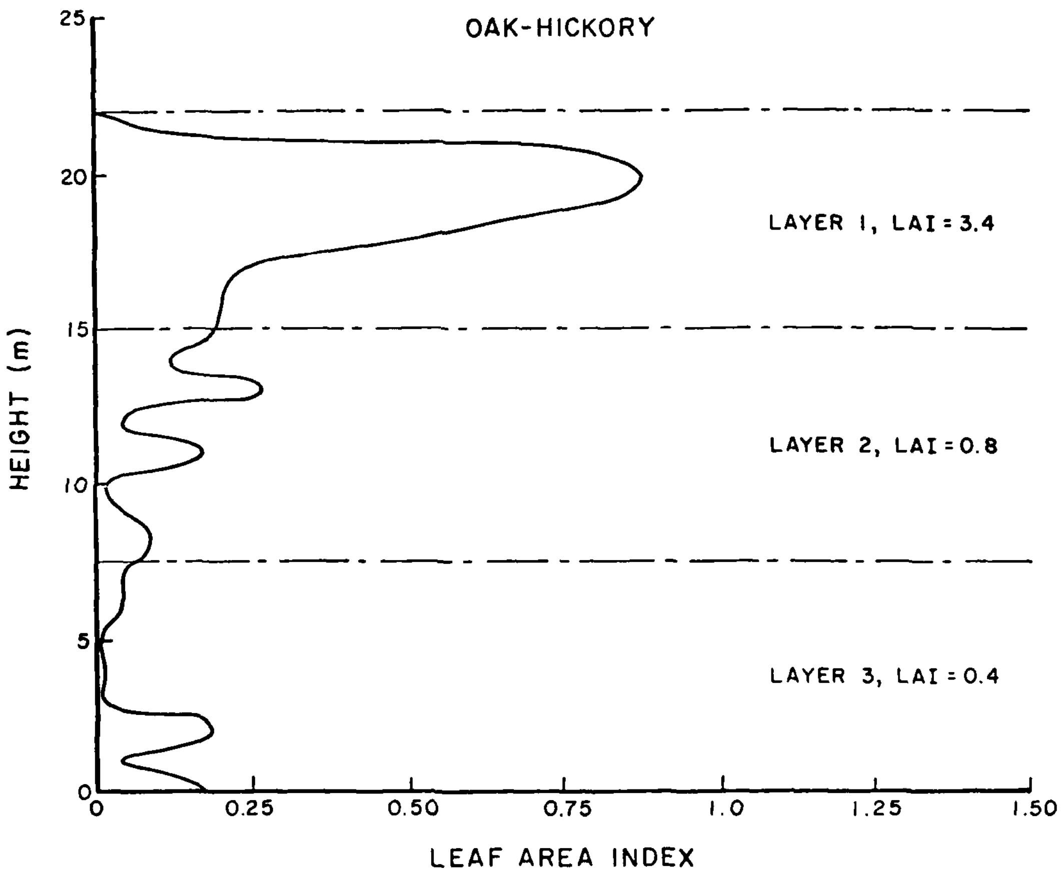


Figure 11. Leaf area index distribution for the oak-hickory canopy

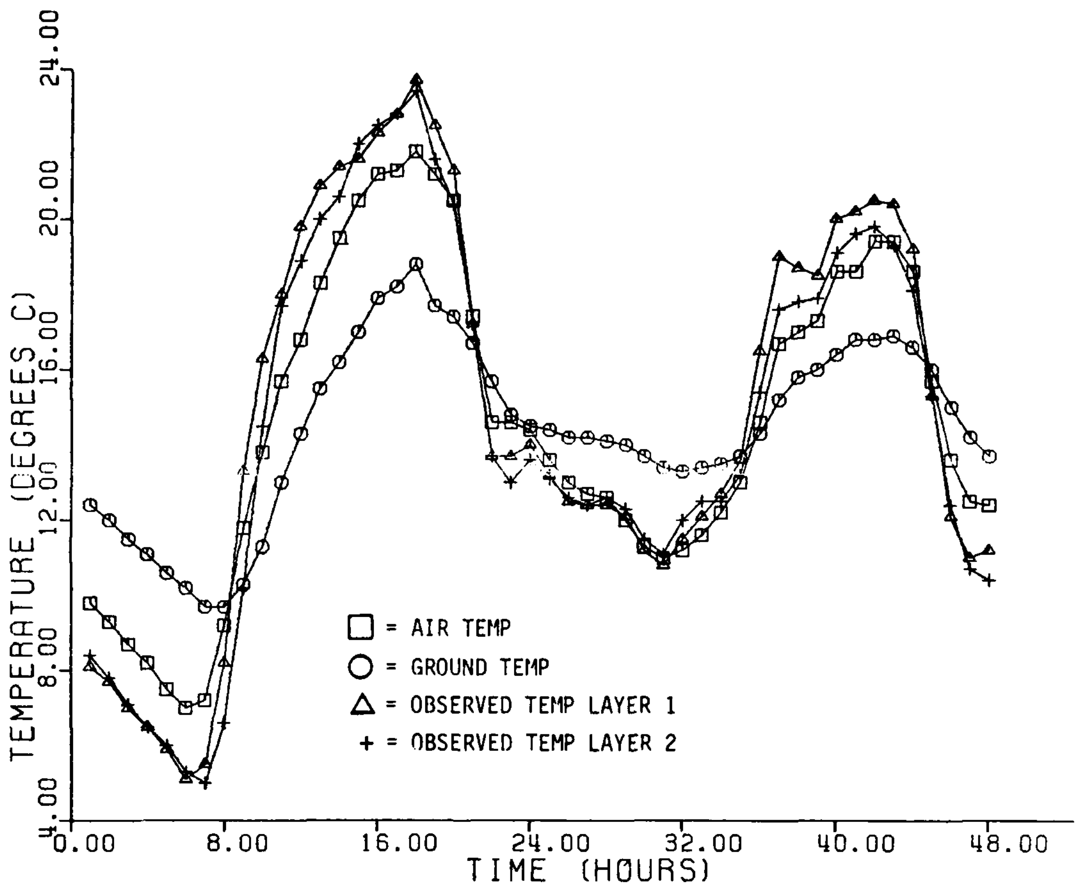


Figure 12. Measured average layer needle temperatures for Douglas-fir plotted with air and ground temperatures for a 48-hour period from August 4 to August 5, 1979; layer 1 and layer 2 needle temperatures measured at 26 m and 20 m respectively

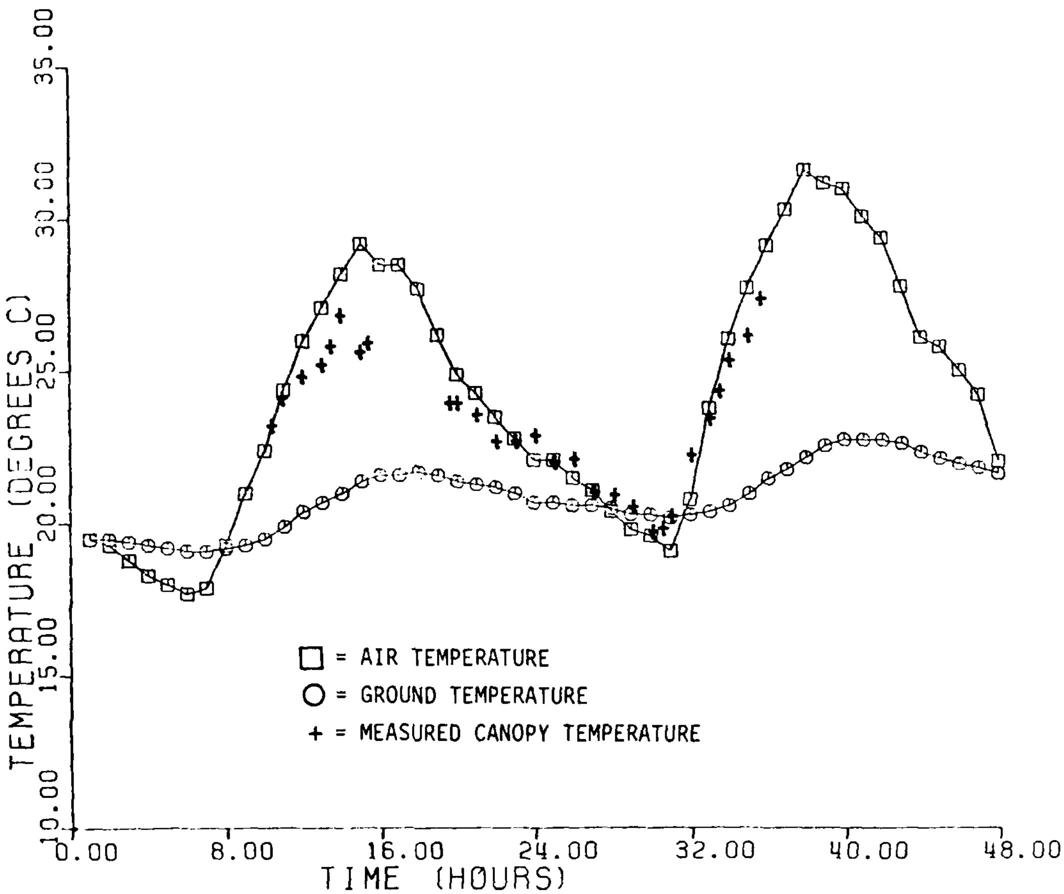


Figure 13. Measured average canopy temperature for oak-hickory plotted with air and ground temperatures for a 48-hour period from August 18 to August 19, 1979; canopy temperatures measured intermittently from 1100 hours on August 18 to 1200 hours on August 19 with a hand-held thermal radiometer

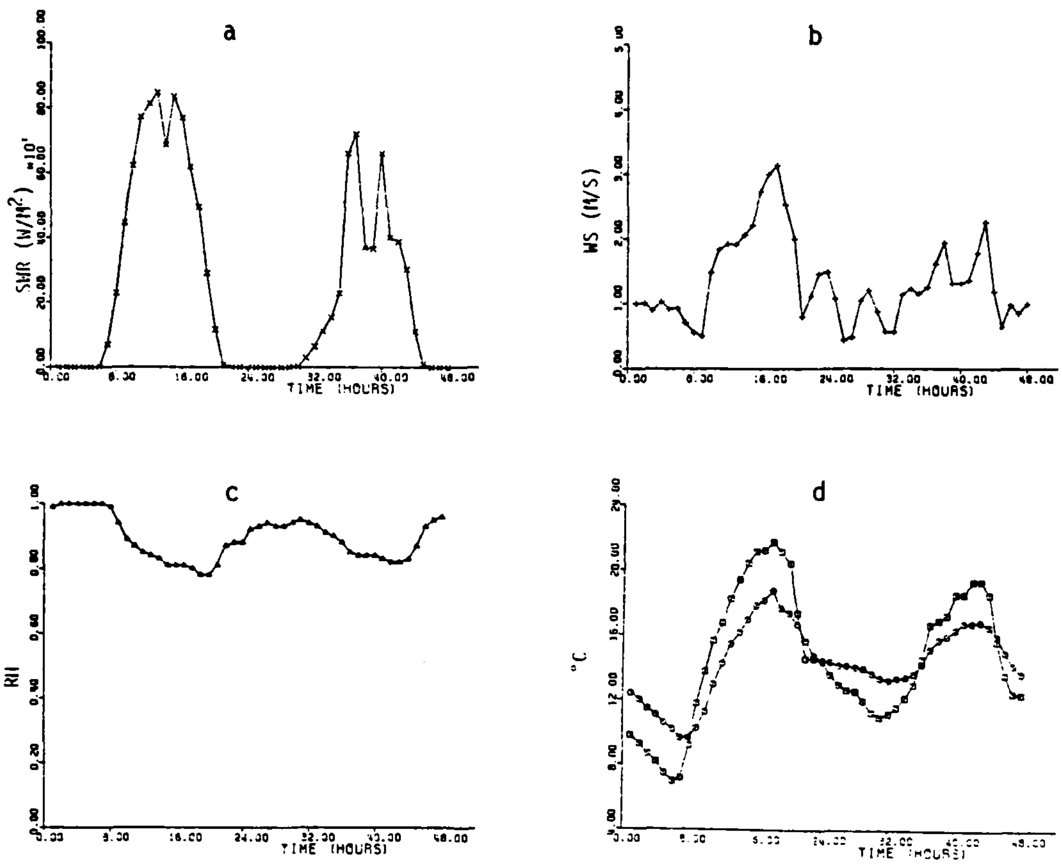


Figure 14. Plots of thermal model environmental input parameters for the Cedar River site from 0000 hr 4 August 1979 to 2400 hr 5 August 1979: a) Global shortwave radiation (SWR), b) Wind speed (WS), c) Relative humidity as estimated from wet and dry bulb temperatures, and d) air temperature (◘) and ground temperature (●)

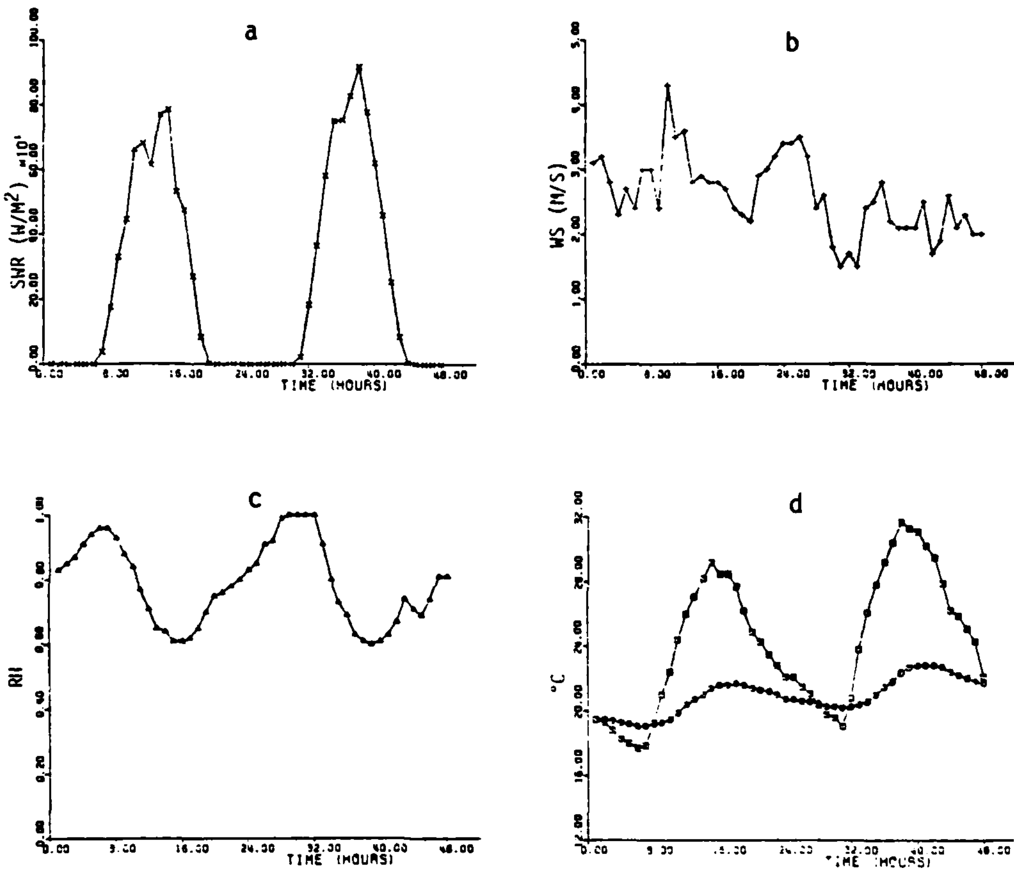


Figure 15. Plots of thermal model environmental input parameters for Walker Branch Site: a) Global shortwave radiation (SWR), b) Wind speed (WS), c) Relative humidity as estimated from wet and dry bulb temperatures, and d) air temperature (◘) and ground temperature (O)

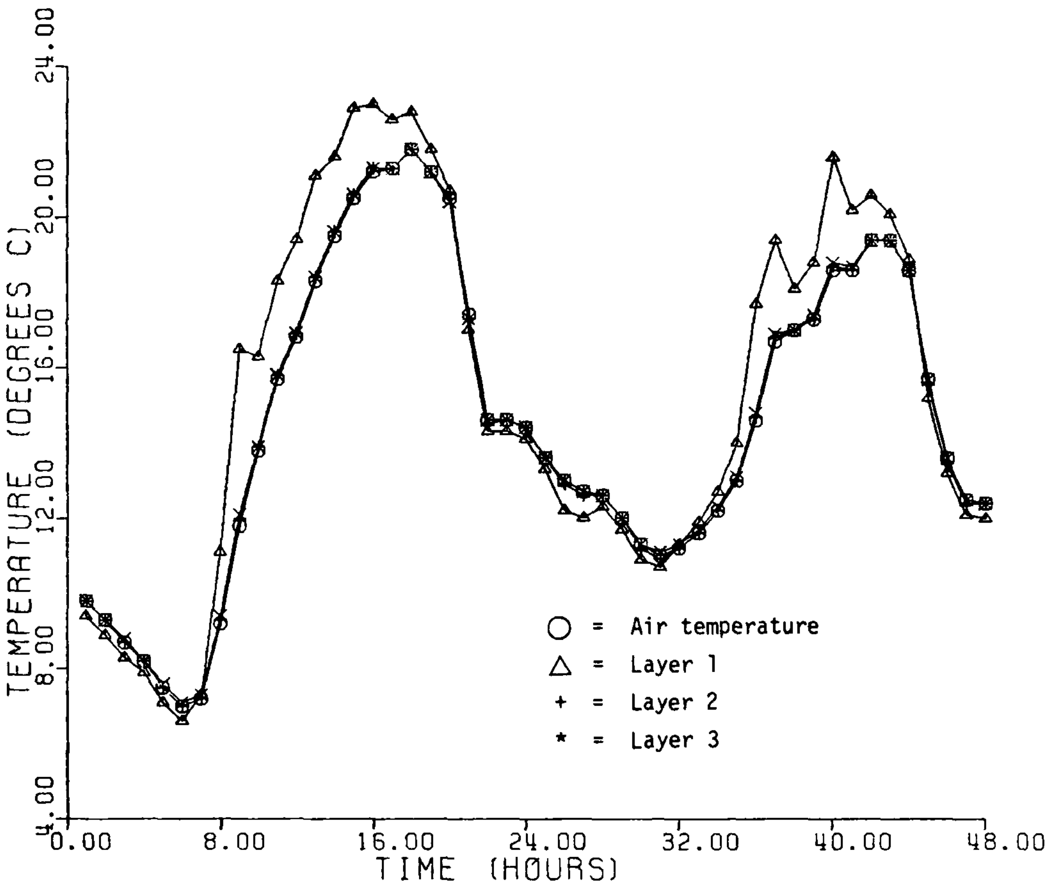


Figure 16. Simulation results for the three-layer Douglas-fir canopy plotted with air temperature for the 48-hour time period from 4-5 August 1979

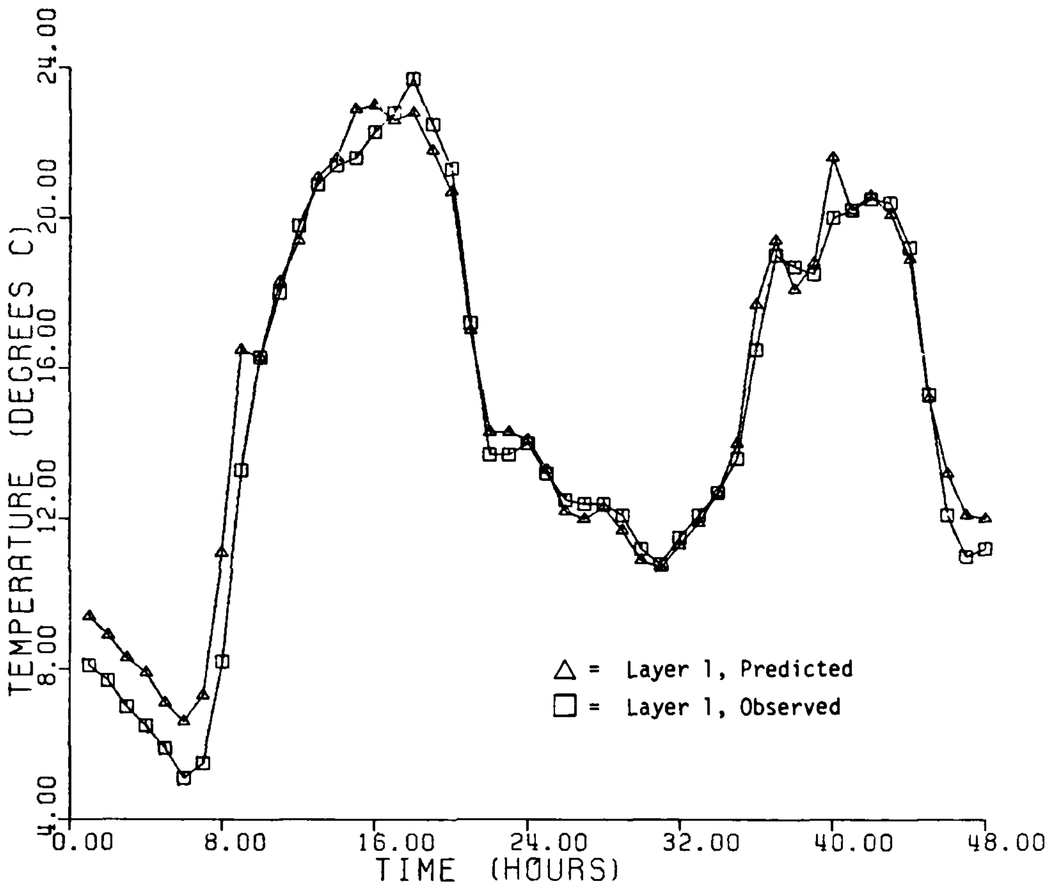


Figure 17. Layer 1 predicted temperatures plotted with average temperatures measured at the 26-m level in the Douglas-fir canopy

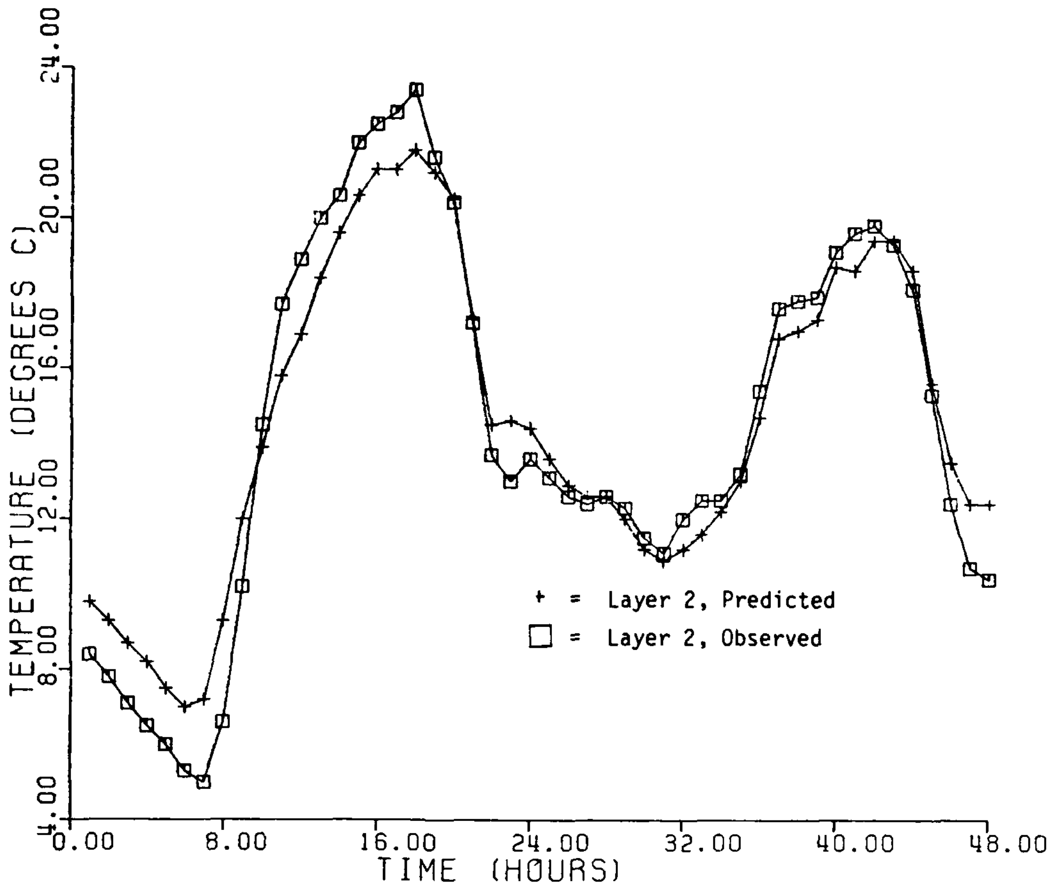


Figure 18. Layer 2 predicted temperature plotted with average temperatures measured at the 20-m level in the Douglas-fir canopy

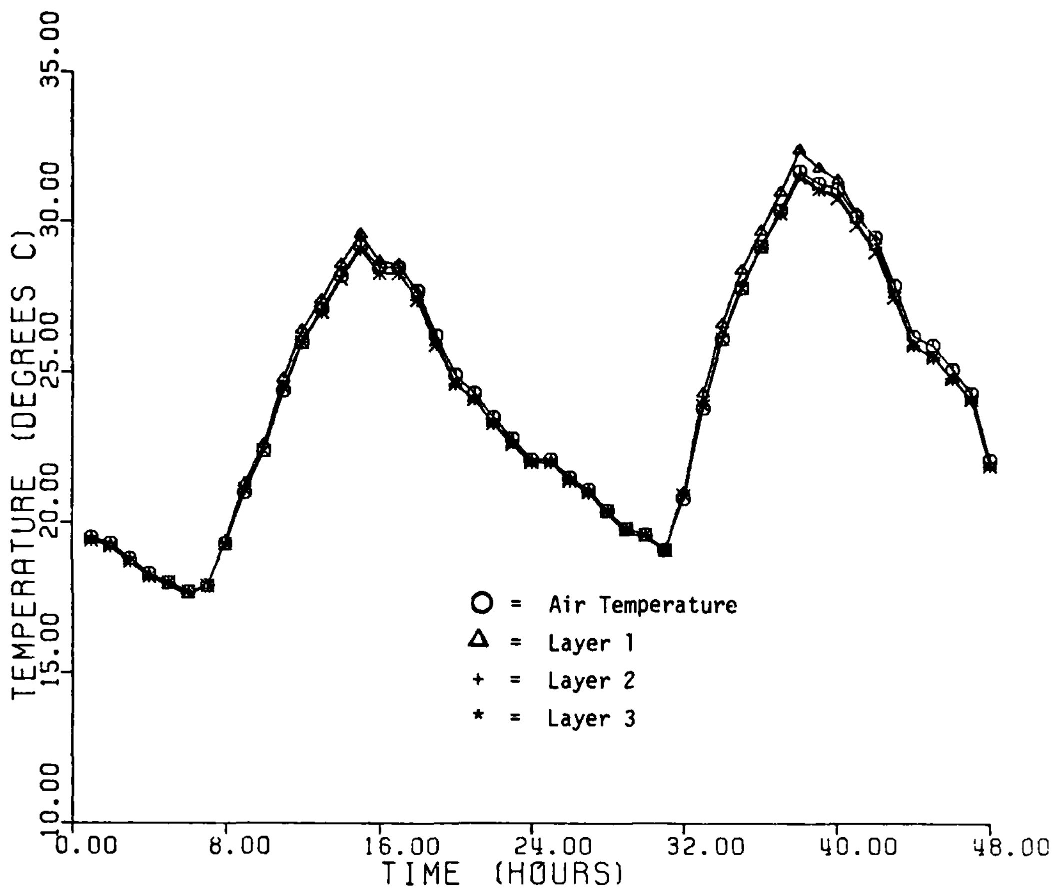


Figure 19. Simulation results for the three-layer oak-hickory canopy plotted with air temperatures for the 48-hour period from 18-19 August 1979

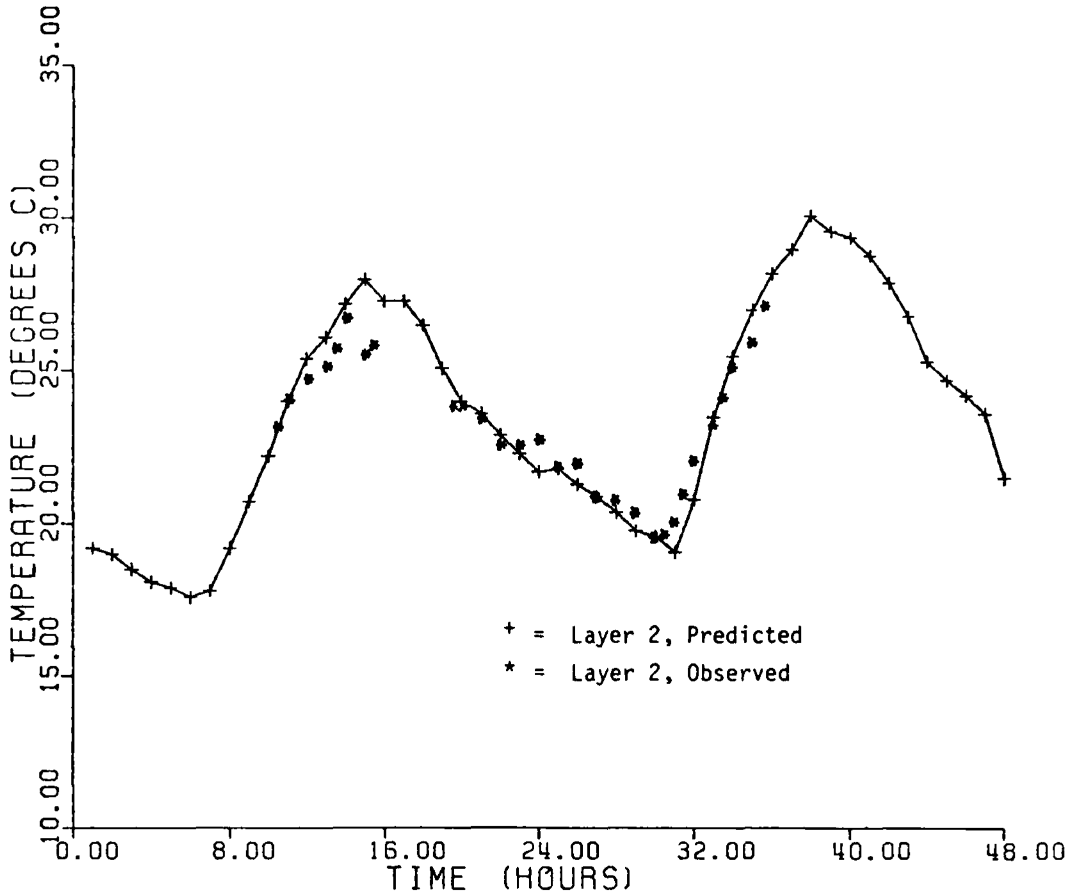


Figure 20. Layer 2 predicted temperature plotted with measured average temperature of oak-hickory canopy; measurements made with a thermal infrared radiometer

APPENDIX A: PROGRAM LISTINGS

TMODEL

```
      PROGRAM TMODEL1(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,
     1TAPE1,TAPE2,TAPE3)
C*************TMODEL--VERSION 2.14.80**************
      COMMON/PARA1/SIG,STA(3),S(3,3),STG(3),X(3),A(3),W(4,9),
     1ALP(3),FMU,TA,TAC,TG,EPS(3),EPSTG,RH,RL
      COMMON/PARA2/BTA,BTG,BX(3),DBX(3),QX(3),DQX(3),RX(3),DRX(3)
      COMMON/ESTIM/FX(3),DFX(3,3)
      COMMON/SENSOR/ERT(9),ERTH(3),EX(9),EXH(3)
       DIMENSION DX(3),SABS(3)
C
C
      SIG=5.6686E-8   $   TOL=.00001
C
C  ---   READ CANOPY GEOMETRY MATRICES   ---
C           FROM TAPE 2
C
C
      READ(2,203) TITLE1,TITLE2,TITLE3
      WRITE(3,203)TITLE1,TITLE2,TITLE3
C         READ W MATRIX:  SENSOR VIEW ANGLE WEIGHTS
C
      DO 2001 N=1,4
        READ(2,202) (W(N,J),J=1,9)
 2001 CONTINUE
C
C  -- READ S MATRIX: LW FLUX TRANSFERS
C
      DO 2000 I=1,3
      READ(2,202)STA(I),(S(I,J),J=1,3),STG(I)
 2000 CONTINUE
C
C ---    READ ABS:  SW FLUX
C
 202  FORMAT(9F7.4)
      READ(2,202) (SABS(N),N=1,3)
 203  FORMAT(1X,3A10)
C
C  ---   DEFINE NOMINAL VALUES FOR MODEL PARAMAMETERS   ---
C
C1000 FORMAT(I4,4F5.0,2X,F5.0)
C1000  FORMAT(I4,2F7.2,2F6.2,2X,F10.2)
C
      ALP(1)=1.0
      ALP(2)=1.0
      ALP(3)=1.0
      EPS(1)=1.0
      EPS(2)=1.0
      EPS(3)=1.0
      EPSTG=1.0
```

```
C
C   ---   READ-IN THE NUMBER OF SIMULATION PERIODS   ---
C
      PRINT 201
  201 FORMAT(//,* ENTER THE NUMBER OF SIMULATION PERIODS DESIRED*/)
      READ*,NSIM
C ---   READ IN CANOPY RESISTANCE  ---
      PRINT 219
  219 FORMAT(/,*ENTER THE CANOPY STOMATAL RESISTANCE FOR THIS RUN*/)
      READ*,RL
      WRITE(6,600)
  600 FORMAT(1H ,4HTIME,4X,3HSWR,15X,1HA,31X,1HB,31X,1HH,23X,2HLE)
      WRITE(6,602)
  602 FORMAT(1H ,17X,1H1,7X,1H2,7X,1H3,7X,1HA,7X,1H1,7X,1H2,7X,1H3,7X,
     .1HG,7X,1H1,7X,1H2,7X,1H3,7X,1H1,7X,1H2,7X,1H3)
    2     CONTINUE
      DO 100 NTIME=1,NSIM
      READ(1,*)ITIME,TA,TG,FMU,RH,GLB
C..... CONVERT FMU IN M/SEC TO CM/SEC.....
      FMU = FMU*100.
      A(1)=GLB*SABS(1)   $   A(2)=GLB*SABS(2)   $  A(3) = GLB*SABS(3)
      TAC=TA
      DO 90 I=1,3
90    X(I)=TA
  50  CALL FEVAL
      DO 20 I=1,3
   20 FX(I)=-FX(I)
      CALL SOLVE(FX,3,DFX,3,DX)
      DO 30 I=1,3
   30 X(I)=X(I)+DX(I)
      DO 40 I=1,3
      DEV=DX(I)
      IF(ABS(DEV) .GT. TOL) GO TO 50
   40 CONTINUE
       CALL WATTS
      WRITE(3,80) ITIME,TA,TG,(ERTH(J),J=1,3)
   80 FORMAT(1H ,I10,2F7.2,3F6.1)
   95 FORMAT(I10,4F10.5)
      BTA=BTA*SIG $ BX(1)=BX(1)*SIG $BX(2)=BX(2)*SIG $ BX(3)=BX(3)*SIG
      BTG=BTG*SIG
C
      WRITE(6,604)ITIME,GLB,(A(I),I=1,3),BTA,(BX(I),I=1,3),BTG,(QX(I),
     .I=1,3),(RX(I),I=1,3)
  604 FORMAT(1H ,I4,15F8.2)
  100 CONTINUE
      STOP
      END
      SUBROUTINE FEVAL
C
      COMMON/PARA1/SIG,STA(3),S(3,3),STG(3),X(3),A(3),W(4,9),
     1ALP(3),FMU,TA,TAC,TG,EPS(3),EPSTG,RH,RL
      COMMON/PARA2/BTA,BTG,BX(3),DBX(3),QX(3),DQX(3),RX(3),DRX(3)
```

```
      COMMON/ESTIM/FX(3),DFX(3,3)
C
      CALL FBTA(TA,BTA)
      CALL BFUNC(EPSTG,TG,BTG,DBTG)
      DO 10 I=1,3
      CALL BFUNC(EPS(I),X(I),BX(I),DBX(I))
      CALL QFUNC(X(I),TAC,FMU,QX(I),DQX(I))
      CALL RFUNC(X(I),TAC,FMU,RL,RH,RX(I),DRX(I))
   10 CONTINUE
      DO 20 IL=1,3
   20 FX(IL)=0.5*ALP(IL)*SIG*(BTA*STA(IL)+BX(1)*S(IL,1)+BX(2)*
     1S(IL,2)+BX(3)*S(IL,3)+BTG*STG(IL))+A(IL)-SIG*BX(IL)+QX(IL)
     2+RX(IL)
      DO 30 I=1,3
      DO 30 J=1,3
   30 DFX(I,J)=0.
      DO 40 IL=1,3
      DO 40 J=1,3
      IF(J.NE.IL) GO TO 35
      DFX(IL,J)=0.5*ALP(IL)*SIG*DBX(J)*S(IL,J)-SIG*DBX(IL)+DQX(IL)+
     1DRX(IL)
      GO TO 40
   35 DFX(IL,J)=0.5*ALP(IL)*SIG*DBX(J)*S(IL,J)
   40 CONTINUE
      RETURN
      END
      SUBROUTINE BFUNC(EPSI,XI,BXI,DBXI)
C
      BXI=EPSI*(XI+273.0)**4.
      DBXI=4.*EPSI*(XI+273.0)**3.
      RETURN
      END
      SUBROUTINE FBTA(TA,BTA)
C
      EPSTA=1.-0.261*EXP(-7.77E-4*TA*TA)
      CALL BFUNC(EPSTA,TA,BTA,DBTA)
      RETURN
      END
      SUBROUTINE QFUNC(XI,TAC,FMU,QXI,DQXI)
C
      IF(FMU.GT.30.) GO TO 10
      HC=0.69775*(20.4+0.2*FMU**0.97)
      GO TO 20
   10 HC=0.69775*(0.95*FMU**0.97)
   20 QXI=(XI-TAC)*(-HC)
```

```
      DQXI=-HC
      RETURN
      END
      SUBROUTINE RFUNC(XI,TAC,FMU,RL,RH,RXI,DRXI)
C
      RNUM=FEX(XI)*1.0E-6-RH*FEX(TAC)*1.0E-6
      RDEN=RL+(1./60.)*(0.04+1.27*FMU**(-0.5))
      RXI1=-697.75*(-0.566*XI+597.3)
      RXI2=RNUM/RDEN
      RXI=RXI1*RXI2
      DRXI=697.75*0.566*RXI2+RXI1*(0.056715E-6*FEX(XI))/RDEN
      RETURN
      END
      SUBROUTINE INVERSE(A,N,D)
C
C  ---   INVERT A 3*3 REAL MATRIX A WHOSE DETERMINANT IS D
C        THE RESULT WILL BE STORED IN A
C
      DIMENSION A(3,3),B(3,3)
C
      D=A(1,1)*A(2,2)*A(3,3)+A(1,2)*A(2,3)*A(3,1)+A(1,3)*A(2,1)*
     1A(3,2)-A(3,1)*A(2,2)*A(1,3)-A(1,1)*A(3,2)*A(2,3)-A(2,1)*
     2A(1,2)*A(3,3)
      B(1,1)=(A(2,2)*A(3,3)-A(2,3)*A(3,2))/D
      B(1,2)=-(A(2,1)*A(3,3)-A(2,3)*A(3,1))/D
      B(1,3)=(A(2,1)*A(3,2)-A(2,2)*A(3,1))/D
      B(2,1)=-(A(1,2)*A(3,3)-A(1,3)*A(3,2))/D
      B(2,2)=(A(1,1)*A(3,3)-A(1,3)*A(3,1))/D
      B(2,3)=-(A(1,1)*A(3,2)-A(1,2)*A(3,1))/D
      B(3,1)=(A(1,2)*A(2,3)-A(1,3)*A(2,2))/D
      B(3,2)=-(A(1,1)*A(2,3)-A(1,3)*A(2,1))/D
      B(3,3)=(A(1,1)*A(2,2)-A(1,2)*A(2,1))/D
      DO 10 I=1,3
      DO 10 J=1,3
   10 A(I,J)=B(I,J)
      RETURN
      END
      FUNCTION FEX(XI)
C
      XX=5.2342*EXP(0.056715*XI)
      FEX=XX
      RETURN
      END
      SUBROUTINE SOLVE(Y,N,A,M,X)
C
```

```
C     DIMENSION Y(N),A(N,M),X(M),ATA(M,M),ATY(M)
      DIMENSION Y(3),A(3,3),X(3),ATA(3,3),ATY(3)
C
      DO 10 I=1,M
      DO 10 J=1,M
      ATA(I,J)=0.
      DO 10 K=1,N
   10 ATA(I,J)=ATA(I,J)+A(K,I)*A(K,J)
      CALL INVERSE(ATA,M,D)
      DO 20 I=1,M
      ATY(I)=0.
      DO 20 J=1,N
   20 ATY(I)=ATY(I)+A(J,I)*Y(J)
      DO 30 I=1,M
      X(I)=0.
      DO 30 J=1,M
   30 X(I)=X(I)+ATA(I,J)*ATY(J)
      RETURN
      END


      SUBROUTINE WATTS
      COMMON/PARA1/SIG,STA(3),S(3,3),STG(3),X(3),A(3),W(4,9),
     1ALP(3),FMU,TA,TAC,TG,EPS(3),EPSTG,RH,RL
      COMMON/SENSOR/ERT(9),ERTH(3),EX(9),EXH(3)
C
      DO 1 N=1,3
      EXH(N)=EPS(N)*SIG*(X(N)+273.)**4
      ERTH(N)=( (EXH(N)/SIG)**0.25) - 273.
1     CONTINUE
C
      DO 2 J=1,9
      EX(J)=SIG*EPS(1)*W(1,J)*(X(1)+273.)**4 +
     1SIG*EPS(2)*W(2,J)*(X(2)+273.)**4+
     2SIG*EPS(3)*W(3,J)*(X(3)+273.)**4+
     3SIG*EPSTG*W(4,J)*(TG+273.)**4
      ERT(J)=( (EX(J)/SIG)**0.25)-273.
2     CONTINUE
      RETURN
      END
```

```
      PROGRAM SCALC(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE1,TAPE2,
     .TAPE3)
C
C*************SCALC--VERSION 2.14.80 ****************
C
C
C...THIS PROGRAM IS EXTRACTED FROM THE TCSM MODEL BY KIMES TO
C...CALCULATE THE SENSOR VIEW WEIGHTING MATRIX W AND THE LONGWAVE
C...RADIATION EXCHANGE MATRIX S FOR A GIVEN CANOPY GEOMETRY.
C...REQUIRED INPUTS ARE LEAF INCLINATION ANGLE AND CORRESPONDING
C...FREQUENCY, CANOPY DENSITY (SLAI) AND LEAF AREA INDEX (FLAI)
C...FOR EACH OF THREE CANOPY LAYERS.
C
C
      COMMON /A/ WV,RH,RL,D(3)
      COMMON /B/ PGAP(3,9), PHIT(3,9),PGAP2(3,9), PHIT2(3,9),STEF
      COMMON/C/COSTA(9,9,18),EMISSV(4),ABSORB(3), ESKY, EGRD, SECTAR(9)
      COMMON/D/CONT(3,5,9),C(3,5,9), SUMT(3,9), KELV, GT, NUSIM, ITIME
      COMMON/E/AT,THETA(9),PHI(18),XLF(9), YLF(9), ZLF(9), XS(9,18)
      COMMON/F/YS(9,18),ZS(9), CEDTR, B, FREQD(9,3) , WA(15),EPS
      COMMON/G/NSIG,N, ITMAX
      COMMON /H/ INDEX1,TITLE(8)
      COMMON /I/ X(3)
      COMMON /J/ THERM,THMLEX,CONVEC,TRANS
      COMMON/S/ ABSOL(3)
C
C...READ AND ASSIGN THE INPUT DATA
C
      NUSIM=-1
      INDEX1=0
   76 IF(INDEX1.EQ.NUSIM)STOP
      CALL INPUTDA
      IF(INDEX1.GT.1) GO TO 95
C
C...CALCULATE THE CANOPY GEOMETRY COEFFICIENTS
C
      CALL CANGEOM
C
      CALL WMAT(TITLE)
C
C...CALCULATE THE SIN THETA FACTORS FOR ALL SOURCE ANGLE-LEAF ANGLE
C   PURMUTATIONS.
C
      CALL DEVANG
C
```

```
C...CALCULATE THE NORMALIZING FACTOR FOR THE RELATIVE SIZES OF SOURCE SECTORS
C
      CALL SECTOR
   95 CONTINUE
C
C...CALCULATE THE THERMAL RADIATION COEFFICIENTS
C
      CALL SETUP
C
C...CALCULATE THE AVERAGE LEAF TEMPERATURE WITHIN EACH LAYER.
C
C...DISPLAY THE OUTPUT
C
      CALL OUTDAT
      GO TO 76
      END
      SUBROUTINE INPUTDA
C
C
C...SUBROUTINE INPUTDA READS AND ASSIGNS THE INPUT DATA
C
C
      COMMON/GEO/ PHIT1(3,9),FLAI(3,1),SLAI(3,1),AXLFA(19,3),AYLFA(19,3)
      COMMON /A/ WV,RH,RL,D(3)
      COMMON /B/ PGAP(3,9), PHIT(3,9),PGAP2(3,9), PHIT2(3,9),STEF
      COMMON/C/COSTA(9,9,18),EMISSV(4),ABSORB(3), ESKY, EGRD, SECTAR(9)
      COMMON/D/CONT(3,5,9),C(3,5,9), SUMT(3,9), KELV, GT, NUSIM, ITIME
      COMMON/E/AT,THETA(9),PHI(18),XLF(9), YLF(9), ZLF(9), XS(9,18)
      COMMON/F/YS(9,18),ZS(9), CEDTR, B, FREQD(9,3) , WA(15),EPS
      COMMON/G/NSIG,N, ITMAX
      COMMON /H/ INDEX1,TITLE(8)
      COMMON /I/ X(3)
      COMMON /J/ THERM,THMLEX,CONVEC,TRANS
      COMMON /N/ STOR(3)
      COMMON/S/ ABSOL(3)
C
C...TEST FOR THE SIMULATION NUMBER AND SKIP TO THE APPROPRIATE INPUT DATA
C
      IF (INDEX1.EQ.0) GO TO 99
      IF(INDEX1.EQ.NUSIM) STOP
   99 CONTINUE
C
C...ASSIGN THE STEFFAN BOLTZMANN CONSTANT WATTS/M**2*K**4
C
      STEF=5.6686E-8
```

```
C
C...ASSIGN THE CONVERSION FACTOR FOR KELVIN-DEGREES
C
      B= 273.0
C
C...READ THE AVERAGE THERMAL EMISSIVITY COEFFICIENTS FOR THE 3 VEGETAION LAYERS
C     (1,2,3) AND THE GROUND(4).
C
      READ(1,199)(TITLE(N),N=1,8)
      IF(EOF(1).NE.0.)STOP
  199 FORMAT(8A10)
C
C
C
C
C...READ THE CANOPY GEOMETRY FREQUENCY DISTRIBUTIONS OF THE ELEMENTS
C   IN LAYERS 1,2,3. AXLFA REPRESENTS THE INCLINATION ANGLES 0-90
C   (5 DEGREE INTERVALS) AND AYLFA REPRESENTS THE CORRESPONDING
C   FREQUENCY. SLAI AND FLAI ARE EACH LAYERS S PARAMETER AND LAI
C   RESPECTIVELY.
C
C
      DO 190 I=1,3
      READ(1,*)(AXLFA(M,I),AYLFA(M,I),M=1,19)
      READ(1,*)SLAI(I,1),FLAI(I,1)
  190 CONTINUE
  101 FORMAT (8F10.5)
      RETURN
      END
      SUBROUTINE OUTDAT
C
C
C...SUBROUTINE OUTPUT FORMATS THE DATA TO BE DISPLAYED.
C
C
      COMMON/SENS/  ELAYT(9),ELAYH(3),ERTT(9),ERTH(3)
      COMMON/GEO/ PHIT1(3,9),FLAI(3,1),SLAI(3,1),AXLFA(19,3),AYLFA(19,3)
      COMMON /A/ WV,RH,RL,D(3)
      COMMON /B/ PGAP(3,9), PHIT(3,9),PGAP2(3,9), PHIT2(3,9),STEF
      COMMON/C/COSTA(9,9,18),EMISSV(4),ABSORB(3), ESKY, EGRD, SECTAR(9)
      COMMON/D/CONT(3,5,9),C(3,5,9), SUMT(3,9), KELV, GT, NUSIM, ITIME
      COMMON/E/AT,THETA(9),PHI(18),XLF(9), YLF(9), ZLF(9), XS(9,18)
      COMMON/F/YS(9,18),ZS(9), CEDTR, B, FREQD(9,3) , WA(15),EPS
      COMMON/G/NSIG,N, ITMAX
      COMMON /H/ INDEX1,TITLE(8)
```

```
      COMMON /I/ X(3)
      COMMON /J/ THERM,THMLEX,CONVEC,TRANS
      COMMON /K/ TT1(3),TT2(3),TT3(3),TT4(3)
      COMMON /N/ STOR(3)
      COMMON /L/ TEMP(3)
      COMMON/S/ ABSOL(3)
      DIMENSION S(3,5)
C
C
C...WRITE THE CALCULATED GEOMETRY FOR EACH LAYER
C
      DO 319 I=1,3
      WRITE(2,320) I
  320 FORMAT (///,* THE COMPONENT ANGLE COMPUTATIONS FOR LAYER *.I1,/)
      WRITE(2,321) FLAI(I,1),SLAI(I,1)
  321 FORMAT ( * LAI = *,F4.2,4X,* S= *,F4.2,/)
      WRITE(2,322) (AXLFA(M,I),AYLFA(M,I),M=1,19)
  322 FORMAT( * XLFA,YLFA *,/,(2X,16F8.3))
      WRITE(2,323) (PGAP(I,M),M=1,9)
  323 FORMAT(//,* PGAP FOR 1-9 INCLINATION INTERVALS*,9F8.3)
  319 CONTINUE
C
C...WRITE THE CALCULATED THERMAL CONTRIBUTIONS COEFFICIENTS
C
      WRITE(2,302)
  302 FORMAT(1X,/,* THE PROPORTION OF RADIANCE AREA CONTRIBUTED BY
     $A SECTOR OF THE 9 BANDS(1-9) DIVIDED BY 18 (SECTORS) ARE=*,/)
      WRITE(2,303)(SECTAR(I),I=1,9)
  303 FORMAT(10X,9F10.5,//)
      WRITE(2,40)
   40 FORMAT (1X,//,* THE BAND-PGAP-PHIT-COEFFICIENTS FOR THE THERMAL RA
     +DIATION TRANSFERS ARE =*,/)
     DO 39 I=1,3
      WRITE(2,41) I
   41 FORMAT (1X,* THE 9 BAND COEFFICIENTS TO LAYER *,I1,* ARE*)
      DO 39 J=1,5
      WRITE (2,42) J,(CONT(I,J,M),M=1,9)
   42 FORMAT(8X,* FROM LAYER*,I1,2X,9F6.4)
   39 CONTINUE
      WRITE(2,50)
   50 FORMAT (1X,////,* THE FINAL THERMAL RADIATION COEFFICIENTS ARE AS FOLLOWS
     +*,/)
      DO 49 MXX=1,3
      DO 49 NXX = 1,5
      S(MXX,NXX) = 0.0
```

```
   49  CONTINUE
       DO 51 I=1,3
       WRITE(2,52) I
    52 FORMAT (1X,* THE THERMAL RADIATION CONTRIBUTION TO LAYER *,I1,* FO
      +R EACH OF THE 9 LEAF INCLINATIONS ARE*)
       DO 51 J=1,5
       WRITE (2,53)J,(C(I,J,M),M=1,9)
       DO 51 K=1,9
       S(I,J) = S(I,J)+C(I,J,K)*FREQD(K,I)
    53 FORMAT (8X,* FROM LAYER*,I1,2X,9E10.3)
    51 CONTINUE
       DO 55 IXX = 1,3
       WRITE(3,505)(S(IXX,JXX),JXX=1,5)
  505    FORMAT(5F7.4)
       WRITE(6,503)(S(IXX,JXX),JXX=1,5)
  503   FORMAT(1H ,5F10.4)
    55 CONTINUE
       RETURN
       END
       SUBROUTINE SETUP
C
C
C...SUBROUTINE SETUP PRE-CALCULATES AND PRE-ARRANGES MANY OF THE THERMAL
C   COEFFICIENTS NEEDED FOR THE FINAL ENERGY BUDGETS WHICH ARE PLACED INTO THE
C   ZSYSTM ROUTINE.
C
C
       COMMON /A/ WV,RH,RL,D(3)
       COMMON /B/ PGAP(3,9), PHIT(3,9),PGAP2(3,9), PHIT2(3,9),STEF
       COMMON/C/COSTA(9,9,18),EMISSV(4),ABSORB(3), ESKY, EGRD, SECTAR(9)
       COMMON/D/CONT(3,5,9),C(3,5,9), SUMT(3,9), KELV, GT, NUSIM, ITIME
       COMMON/E/AT,THETA(9),PHI(18),XLF(9), YLF(9), ZLF(9), XS(9,18)
       COMMON/F/YS(9,18),ZS(9), CEDTR, B, FREQD(9,3) , WA(15),EPS
       COMMON/G/NSIG,N, ITMAX
       COMMON /H/ INDEX1,TITLE(8)
C
C
C...FOR EACH LAYER CALCULATE THE BAND-PGAP-PHIT COEFFICIENTS NEEDED FOR EACH
C   LAYERS THERMAL RADIATION CONTRIBUTION TO A  SPECIFIC LAYER.
C
C
       DO 20 I=1,9
C
C
C...CONTRIBUTION COEFFICIENTS TO LAYER 1
```

```
C
C
C.....FROM SKY
C
      CONT(1,1,I)= PGAP2(1,I)
C
C.....FROM LAYER 1
C
      CONT(1,2,I)= 2.*PHIT2(1,I)
C
C.....FROM LAYER 2
C
      CONT(1,3,I)= PGAP2(1,I)-PGAP2(1,I)*PGAP(2,I)
C
C.....FROM LAYER 3
C
      CONT(1,4,I)= PGAP2(1,I)*PGAP(2,I)-PGAP2(1,I)*PGAP(2,I)*PGAP(3,I)
C
C.....FROM GROUND
C
      CONT(1,5,I)= PGAP2(1,I)*PGAP(2,I)*PGAP(3,I)
C
C
C...CONTRIBUTION COEFFICIENTS TO LAYER 2
C
C
C.....FROM SKY
C
      CONT(2,1,I)= PGAP(1,I)*PGAP2(2,I)
C
C.....FROM LAYER 1
C
      CONT(2,2,I)= PGAP2(2,I)-PGAP2(2,I)*PGAP(1,I)
C
C.....FROM LAYER 2
C
      CONT(2,3,I)= 2.*PHIT2(2,I)
C
C.....FROM LAYER 3
C
      CONT(2,4,I)= PGAP2(2,I)-PGAP2(2,I)*PGAP(3,I)
C
C.....FROM GROUND
C
      CONT(2,5,I)= PGAP2(2,I)*PGAP(3,I)
```

```
C
C
C...CONTRIBUTION COEFFICIENTS TO LAYER 3
C
C
C.....FROM SKY
C
      CONT(3,1,I)= PGAP(1,I)*PGAP(2,I)*PGAP2(3,I)
C
C.....FROM LAYER 1
C
      CONT(3,2,I)= PGAP2(3,I)*PGAP(2,I)-PGAP2(3,I)*PGAP(2,I)*PGAP(1,I)
C
C.....FROM LAYER 2
C
      CONT(3,3,I)= PGAP2(3,I)-PGAP2(3,I)*PGAP(2,I)
C
C.....FROM LAYER 3
C
      CONT(3.4,I)= 2.*PHIT2(3,I)
C
C.....FROM GROUND
C
      CONT(3,5,I)= PGAP2(3,I)
   20 CONTINUE
C
C
C...NOW FORM THE EQUATION COEFFICIENTS FOR THE CONTRIBUTED THERMAL RADIANT
C   ENERGY TO EACH LAYER AND FOR EACH LEAF INCLINATION ANGLE WITHIN A LAYER.
C
C
      CALL SET03(C,3,5,9)
C
C...THERMAL RADIATION CONTRIBUTION TO LAYER N
C
      DO 30 N=1,3
C
C...FOR EACH LEAF INCLINATION ANGLE INTERVAL
C
      DO 30 I= 1,9
C
C...SUM EACH SECTORS RADIATION CONTRIBUTION (9 BANDS CONTAINING 18 SECTORS)
C
      DO 30 J=1,9
      DO 30 K=1,18
```

```
C
C...ABSORBED THERMAL RADIATION CONTRIBUTED BY SKY
C
      C(N,1,I)= C(N,1,I) + SECTAR(J)*CONT(N,1,J)
     +*COSTA(I,J,K)
C
C...ABSORBED THERMAL RADIATION CONTRIBUTED BY LAYER 1
C
      C(N,2,I)= C(N,2,I) + SECTAR(J)*CONT(N,2,J)
     +*COSTA(I,J,K)
C
C...ABSORBED THERMAL RADIATION CONTRIBUTED BY LAYER 2
C
      C(N,3,I)= C(N,3,I) + SECTAR(J)*CONT(N,3,J)
     +*COSTA(I,J,K)
C
C...ABSORBED THERMAL RADIATION CONTRIBUTED BY LAYER 3
C
      C(N,4,I)= C(N,4,I) + SECTAR(J)*CONT(N,4,J)
     +*COSTA(I,J,K)
C
C...ABSORBED THERMAL RADIATION CONTRIBUTED BY THE GROUND
C
      C(N,5,I)= C(N,5,I) + SECTAR(J)*CONT(N,5,J)
     +*COSTA(I,J,K)
   30 CONTINUE
      RETURN
      END
      SUBROUTINE DEVANG
C
C
C...SUBROUTINE DVANG CALCULATES THE COS(ANGLE) DEVIATION
C   ANGLE OF ALL LEAF INCLINATIONS SOURCE ORIENTAIONS PERMUTATIONS. THE THEORY
C   IS BASED ON THE EXISTENCE OF PLANE ELEMENTS AS USED IN THE SRVC MODEL.
C
C
      COMMON /A/ WV,RH,RL,D(3)
      COMMON /B/ PGAP(3,9), PHIT(3,9),PGAP2(3,9), PHIT2(3,9),STEF
      COMMON/C/COSTA(9,9,18),EMISSV(4),ABSORB(3), ESKY, EGRD, SECTAR(9)
      COMMON/D/CONT(3,5,9),C(3,5,9), SUMT(3,9), KELV, GT, NUSIM, ITIME
      COMMON/E/AT,THETA(9),PHI(18),XLF(9), YLF(9), ZLF(9), XS(9,18)
      COMMON/F/YS(9,18),ZS(9), CEDTR, B, FREQD(9,3) , WA(15),EPS
      COMMON/G/NSIG,N, ITMAX
      INTEGER SB,SS
      CEDTR= 0.017453293
```

```
C
C...CALCULATE INCLINATIN ANGLES IN RADIANS
C
      THETA(1)= 5. * CEDTR
      DO 10 I=1,8
      THETA(I+1)= THETA(I) + 10.0 * CEDTR
   10 CONTINUE
C
C...CALCULATE AZIMUTH ANGLES IN RADIANS
C
      PHI(1)= 10.*CEDTR
      DO 20 I=1,17
      PHI(I+1)= 20.*CEDTR+PHI(I)
   20 CONTINUE
C
C...CALCULATE ALL THE DIRECTION COSINES OF SOURCE SECTORS
C
      DO 40 I=1,9
      ZS(I)=SIN(THETA(I))
      DO 40 J=1,18
      XS(I,J)=COS(THETA(I))*COS(PHI(J))
      YS(I,J)= COS(THETA(I))*SIN(PHI(J))
   40 CONTINUE
C
C...CALCULATE THE DIRECTION COSINES FOR THE NORMAL VECTOR OF ALL PLANAR LEAF
C   INCLINATION ANGLES ASSUMING THAT THE AZIMUTH ANGLE IS EQUAL TO ZERO DEGREES.
C
      DO 30 I= 1,9
      XLF(I)= -SIN(THETA(I))
      YLF(I)= 0.0
      ZLF(I)= COS(THETA(I))
   30 CONTINUE
C
C...CALCULATE THE ABSOLUTE VALUE OF THE DOT PRODUCTS OF ALL SOURCE-LEAF
C   ANGLE PERMUTATIONS. THIS VALUE IS EQUAL TO THE COSINE FACTOR DESIRED.
C
      DO 50 LI=1,9
      DO 50 SB=1,9
      DO 50 SS= 1,18
      DOT= (XLF(LI)*XS(SB,SS)+YLF(LI)*YS(SB,SS)+ZLF(LI)*ZS(SB))
      COSTA(LI,SB,SS)= ABS (DOT)
   50 CONTINUE
      RETURN
      END
      SUBROUTINE CANGEOM
```

```
C
C
C...SUBROUTINE CANGEOM CALCULATES THE CANOPY GEOMETRY COEFFICIENTS.
C...THE SUBROUTINE CANGEOM CALLS SUBROUTINE SRVCMOD WHICH IS A MODIFIED
C   PORTION OF THE SRVC MODEL THAT CALCULATES THE CANOPY GEOMETRY
C   PARAMETERS.
C
C
      COMMON/GEO/ PHIT1(3,9),FLAI(3,1),SLAI(3,1),AXLFA(19,3),AYLFA(19,3)
      COMMON /A/ WV,RH,RL,D(3)
      COMMON /B/ PGAP(3,9), PHIT(3,9),PGAP2(3,9), PHIT2(3,9),STEF
      COMMON/C/COSTA(9,9,18),EMISSV(4),ABSORB(3), ESKY, EGRD, SECTAR(9)
      COMMON/D/CONT(3,5,9),C(3,5,9), SUMT(3,9), KELV, GT, NUSIM, ITIME
      COMMON/E/AT,THETA(9),PHI(18),XLF(9), YLF(9), ZLF(9), XS(9,18)
      COMMON/F/YS(9,18),ZS(9), CEDTR, B, FREQD(9,3) , WA(15),EPS
      COMMON/G/NSIG,N, ITMAX
      CALL SRVCMOD
      DO 10 I=1,3
      DO 10 M=1,9
C
C...TRANSFER IDENTICAL ARRAYS PHIT AND PHIT1. PHIT CONTAINS THE
C   PROBABILITY OF HIT COEFFICIENTS FOR EACH VIEW ANGLE AND LAYER
C   PERMUTAION
C
      PHIT(I,M)=PHIT1(I,M)
C
C...CALCULATE THE PROBABILITY OF GAP (PGAP) FOR ALL PERMUTATIONS.
C
      PGAP(I,M)=1.-PHIT(I,M)
C
C...CALCULATE THE PROBABILITY OF GAP AND HIT FOR THE HALF LAYERS(PGAP2,PHIT2)
C   FOR ALL PERMUTATIONS.
C
      PGAP2(I,M)= SQRT(PGAP(I,M))
      PHIT2(I,M)=1.-PGAP2(I,M)
   10 CONTINUE
C
C...OBTAIN THE FREQUENCY OF OCCURENCE (FREQD) OF ELEMENTS IN EACH OF THE
C...NINE INCLINATION INTERVALS FOR EACH LAYER.
C
      DO 15 J=1,3
      ADD=0.0
      DO 20 N=1,9
      FREQD(N,J)= AYLFA(2*N,J)
      ADD=ADD + FREQD(N,J)
```

```
   20 CONTINUE
      DO 25 K=1,9
      FREQD(K,J)=FREQD(K,J)/ADD
   25 CONTINUE
   15 CONTINUE
      RETURN
      END
      SUBROUTINE SRVCMOD
C
C
C...SUBROUTINE SRVCMOD IS A MODIFIED VERSION OF A PORTION OF THE SRVC
C   MODEL WHICH CALCUALTES THE GEOMETRIC PARAMETERS OF A CANOPY.
C
C
      COMMON/GEO/ PHIT1(3,9),FLAI(3,1),SLAI(3,1),AXLFA(19,3),AYLFA(19,3)
      DIMENSION NANGLE(3,3),FLA(3,3,10),THETA(10)
      DIMENSION PHIT(3,3,10),MTP(3),OPM(10),XK(9),XLFA(19)
      DIMENSION YLFA(19), DM(17), F(19), OP(9)
      REAL INCLF
C
C
C....GENERAL SIMULATION CONSTRAINTS                                      SRVC
C
      CEPIO2= 1.57079632
      CE2PI=  6.28318530
      CE1PI=  3.14159265
      CEDTR=.017453293
      CERTD= 57.2957795
      CEMTR= .00029088821
      NBANDS=9
      NMAT=1
      NLAY=3
      BANDW=90/NBANDS                                                    SRVC
C
C....PARAMETER INITIALIZATION AND CONVERSION                             SRVC
C
      NSOUR=NBANDS+1                                                     SRVC
      BANDW=BANDW*CEDTR                                                  SRVC
C
C....COEFFICIENTS FOR DIFFUSE RADIATION VECTORS                          SRVC
C
      ALPHA2=0.                                                          SRVC
      SINA2=0.                                                           SRVC
      DO 2 I=1,NBANDS                                                    SRVC
      SINA1=SINA2                                                        SRVC
```

```
      ALPHA2=ALPHA2+BANDW                                               SRVC
      SINA2=SIN(ALPHA2)                                                 SRVC
      XK(I)=SINA2*SINA2-SINA1*SINA1                                     SRVC
    2 CONTINUE
C
C....SOURCE DIRECTION INCLINATION ANGLES                                SRVC
C
      TOTAL=0.                                                          SRVC
      THETA(1)=(BANDW/2.)-BANDW                                         SRVC
      DO 3 I=1,NBANDS                                                   SRVC
      THETA(I+1)=THETA(I)+BANDW                                         SRVC
    3 CONTINUE
C
C....CANOPY GEOMETRY.  EACH CANOPY LAYER IS COMPOSED OF ONE OPTICAL     SRVC
C....MATERIAL WHICH MAY BE SPECIFIED AND UNIQUE GEOMETRICAL PROPERTIES. SRVC
C....CANOPY GEOMETRIC PARAMETERS CONSIST OF (1)LEAF ANGLE FREQUENCY     SRVC
C....DISTRIBUTION FUNCTION DENOTED BY XLFA AND YLFA (2)LEAF AREA INDEX  SRVC
C....DENOTED BY FLAI AND (3)CANOPY DENSITY DENOTED BY SLAI.  XLFA (DEG) SRVC
C....AND YLFA MUST BE SPECIFIED AT AN ODD NUMBER (NANG) OF EVENLY SPACED SRVC
C....POINTS.  FLAI IS NON-NEGATIVE AND SLAI RANGES BETWEEN 0 AND 1.     SRVC
C
      DELF=10.*CEDTR                                                    SRVC
      DO 350 IL=1,NLAY                                                  SRVC
      NANG=19
C
C...ASSIGN THE NUMBER OF MATERIALS IN ANY GIVEN LAYER
C
      IMAT=1
      MTP(IL) = IMAT                                                    SRVC
      IMAT1=IMAT
      DO 351 J=1,IMAT1
      IMAT = J
      DO 41 MM=1,NANG
      XLFA(MM)=AXLFA(MM,IL)
      YLFA(MM)=AYLFA(MM,IL)
   41 CONTINUE
C
C....INTEGRATE AND NORMALIZE THE LEAF ANGLE FREQUENCY DISTRIBUTION      SRVC
C....FUNCTION USING SIMPSONS RULE--THIS IS TEMPORARILY DENOTED BY F.    SRVC
C....M-1 EQUALLY SPACED INTERVALS OF F ARE THEN DETERMINED AND DENOTED  SRVC
C....BY FLA (M POINTS).  THE TABLE FLA IS USED FOR RANDOMLY SELECTING   SRVC
C....LEAF INCLINATION ANGLES.                                           SRVC
C
      DO 305 I=1,NANG                                                   SRVC
305   XLFA(I)=XLFA(I)*CEDTR                                             SRVC
```

```
      M=((NANG-1)/2)+1                                                    SRVC
      NANGLE(IL,IMAT)=M                                                   SRVC
      CALL TBLR(M,XLFA,YLFA,BM,F)                                         SRVC
      DO 310 IANG=1,M                                                     SRVC
  310 FLA(IL,IMAT,IANG)=DM(IANG)                                          SRVC
C
C
C....NORMALIZE THE INPUT LEAF FREQUENCY DISTRIBUTION FUNCTION TO OBTAIN  SRVC
C....A DENSITY FUNCTION F WHICH IS SPECIFIED AT M POINTS.                SRVC
C
      FTOT=0.                                                             SRVC
      DO 311 I=1,NANG                                                     SRVC
  311 FTOT=FTOT+YLFA(I)                                                   SRVC
      DO 312 I=1,9                                                        SRVC
  312 F(I)=(YLFA(2*I)+YLFA(2*I+1))/FTOT                                   SRVC
      DO 315 I=1,NANG                                                     SRVC
315   XLFA(I)=XLFA(I)*CERTD                                               SRVC
      M=M-1                                                               SRVC
C
C....CALCULATE THE MEAN PROJECTION (OP) IN THE DIRECTION OF THE SOURCE   SRVC
C...(THETA) OF ONE UNIT LEAF AREA WITH INCLINATION INCLF.  THE LEAVES    SRVC
C....AT THIS ANGLE ARE ASSUMED TO BE AZIMUTHALLY ISOTROPIC.              SRVC
C
      DO 330 IANGLE=1,NSOUR                                               SRVC
      INCLF=-5.*CEDTR                                                     SRVC
      DO 320 I=1,9                                                        SRVC
      INCLF=INCLF+DELF                                                    SRVC
  320 CALL COP(INCLF,THETA(IANGLE),OP(I),CEPIO2)
C
C....CALCULATE THE MEAN PROJECTION (OPM) IN THE DIRECTION OF THE SOURCE  SRVC
C....(THETA) OF ONE UNIT LEAF AREA AVERAGED OVER THE CANOPY LEAF ANGLE   SRVC
C....DENSITY FUNCTION F.                                                  SRVC
C
      CALL COPM(F,OP,OPM(IANGLE))                                         SRVC
C
C....CALCULATE THE PROBABILITY OF A HIT (PHIT) FOR A LIGHT RAY WITH      SRVC
C....SOURCE DIRECTION THETA.                                              SRVC
C
      CALL PDENS(IL,IMAT,IANGLE,OPM(IANGLE),THETA,NANGLE,FLA,SLAI,FLAI,
     * PHIT)
  330 CONTINUE                                                            SRVC
  351 CONTINUE
  350 CONTINUE                                                            SRVC
       J=NMAT
      DC 228 I=1,3
```

```
      DO 228 M=1,9
      PHIT1(I,M)=PHIT(I,1,M+1)
  228 CONTINUE
      RETURN
      END                                                               SRVC
      SUBROUTINE COP(ALPHA,BETA,OP,CEPIO2)
C                                                                       COP
C
C....THIS PROGRAM CALCULATES THE MEAN PROJECTION OF A UNIT LEAF AREA IN  COP
C....THE DIRECTION OF THE SOURCE.  THE LEAF IS INCLINED AT AN ANGLE      COP
C....ALPHA AND IS ASSUMED TO BE AZIMUTHALLY ISOTROPIC.
C                                                                       COP
C
C
      OP=COS(ALPHA)*SIN(BETA)                                           COP
      IF(ALPHA.LE.BETA) RETURN                                          COP
C
C....THETAO IS THE LEAF AZIMUTH ANGLE AT WHICH OP BECOMES NEGATIVE AND   COP
C....IS IN THE FIRST QUADRANT.  THE FUNCTION OP IS SYMMETRIC AND HENCE   COP
C....IS AVERAGED OVER LEAF AZIMUTH ANGLES OF 0 TO PI RADIANS.            COP
C
      THETAO=ACOS(TAN(BETA)/TAN(ALPHA))                                 COP
      TANTO=TAN(THETAO)                                                 COP
      OP=OP*(1.+(TANTO-THETAO)/CEPIO2)                                  COP
      RETURN                                                            COP
      END                                                               COP
      SUBROUTINE COPM(G,OP,OPM)                                         COPM
C
C
C....THIS PROGRAM CALCULATES THE MEAN PROJECTION OF A UNIT LEAF AREA IN  COPM
C....THE DIRECTION OF THE SOURCE (OPM) FOR THE SIMULATED CANOPY.  THE    COPM
C....LEAVES OF THE CANOPY ARE ASSUMED TO BE AZIMUTHALLY ISOTROPIC.  THE  COPM
C....OP FUNCTION USED IN THE CALCULATION HAS BEEN PREVIOUSLY DETERMINED  COPM
C....FOR A GIVEN SOURCE DIRECTION FOR LEAF INCLINATION ANGLES OF         COPM
C....5, 15, ..., 85 DEGREES.  G IS THE LEAF INCLINATION ANGLE DENSITY    COPM
C....FUNCTION.                                                          COPM
C                                                                       COPM
C
      DIMENSION OP(9),G(9)                                              COPM
      OPM=0.                                                            COPM
      DO 1 I=1,9                                                        COPM
    1 OPM=OPM+OP(I)*G(I)                                                COPM
      RETURN                                                            COPM
      END                                                               COPM
      SUBROUTINE PDENS(IL,MTYPE,IANGLE,OPM,THETA,NANGLE,FLA,SLAI,FLAI,
```

```
     * PHIT)
C
C
C----THIS PROGRAM COMPUTES THE PROBABILITY THAT LIGHT AT INCIDENT ANGLE  PDENS
C    THETA(IANGLE) INTERACTS WITH MATERIAL TYPE MTYPE WITHIN CANOPY      PDENS
C    LAYER IL.                                                           PDENS
C                                                                        PDENS
C
C    INPUT                                                               PDENS
C      IL                                                                PDENS
C      MTYPE                                                             PDENS
C      IANGLE                                                            PDENS
C      OPM                                                               PDENS
C      SLAI                                                              PDENS
C      FLAI                                                              PDENS
C      THETA                                                             PDENS
C    OUTPUT                                                              PDENS
C      PHIT                                                              PDENS
C                                                                        PDENS
C
      DIMENSION DUM(357),THETA(10)
      DIMENSION NANGLE(3,3),FLA(3,3,10),SLAI(3,3),FLAI(3,3),PHIT(3,3,10) PDENS
      ARG=1.-(SLAI(IL,MTYPE)*OPM/SIN(THETA(IANGLE)))                     PDENS
      IF (ARG.LE.0.) GO TO 1                                             PDENS
      P0=ARG**(FLAI(IL,MTYPE)/SLAI(IL,MTYPE))                            PDENS
      GO TO 2                                                            PDENS
1     P0 = 0.                                                            PDENS
2     CONTINUE                                                           PDENS
      PHIT(IL,MTYPE,IANGLE)=1.-P0                                        PDENS
      RETURN
      END                                                                PDENS
      SUBROUTINE TBLR(M, X, Y, XX, Z)                                    TBLR
C                                                                        TBLR
C
C....THIS PROGRAM FINDS THE INTEGRAL Z(X) OF THE FUNCTION Y(X) FROM X(1) TBLR
C....TO X(2M-1) USING SIMPSONS RULE.  THE INTEGRAL Z(X) IS NORMALIZED TO TBLR
C....1.0 AT X(2M-1).  THE TABLE OF Z VERSUS X IS THEN INVERTED TO DETER- TBLR
C....MINE X AS A FUNCTION OF Z AT M REGULARLY SPACED POINTS ALONG Z.     TBLR
C                                                                        TBLR
C
C    INPUT VARIABLES                                                     TBLR
C      M  = DESIRED NUMBER OF REGULARLY SPACED POINTS ALONG Z            TBLR
C      X  = SPECIFIED AT 2M-1 POINTS                                     TBLR
C      Y  = SPECIFIED AT 2M-1 POINTS                                     TBLR
C    OUTPUT VARIABLES                                                    TBLR
```

```
C       XX = THE TABLE OF X VALUES FOR M REGULARLY SPACED POINTS          TBLR
C            (M-1 INTERVALS) ALONG Z.                                     TBLR
C       Z  = THE NORMALIZED INTEGRAL OF Y AT X(1), X(3), ..., X(2M-1).    TBLR
C                                                                         TBLR
C
      DIMENSION X(19),Y(19),Z(10),XI(10),XX(10)                           TBLR
C
C....SIMPSONS RULE INTEGRATION                                            TBLR
C
10    Z(1) = 0.0                                                          TBLR
      DX = X(2) - X(1)                                                    TBLR
20    DO 50 J = 2,M                                                       TBLR
      J0 = 2*J - 3                                                        TBLR
30    J1 = 2*J - 2                                                        TBLR
      J2 = 2*J - 1                                                        TBLR
40    Z(J) = Z(J - 1) + DX*(Y(J0) +4.*Y(J1) + Y(J2))/3.0                  TBLR
50    XI(J) = X(J2)                                                       TBLR
      XI(1)=X(1)                                                          TBLR
C
C....NORMALIZE INTEGRAL Z(X)                                              TBLR
C
60    DO 70 J = 1,M                                                       TBLR
70    Z(J) = Z(J)/Z(M)                                                    TBLR
C
C....FIND X AT M REGULARLY SPACED POINTS ALONG Z.                         TBLR
C
      XX(1) = X(1)                                                        TBLR
      EM = M - 1                                                          TBLR
      F = 1.0/EM                                                          TBLR
      JS=2                                                                TBLR
80    DO 120 K = 2,M                                                      TBLR
      ZT = K - 1                                                          TBLR
      ZT = ZT*F                                                           TBLR
90    DO 110 J =JS,M                                                      TBLR
      IF(Z(J) - ZT) 110, 100, 100                                         TBLR
100   G = (ZT - Z(J - 1))    /(Z(J) - Z(J - 1))                           TBLR
      XX(K) = XI(J - 1) + G*(XI(J) - XI(J - 1))                           TBLR
      GO TO 115                                                           TBLR
110   CONTINUE                                                            TBLR
115   JS=J                                                                TBLR
120   CONTINUE                                                            TBLR
      RETURN                                                              TBLR
      END                                                                 TBLR
      SUBROUTINE SECTOR
C
```

```
C
C...SUBROUTINE SECTOR CALCULATES THE NORMALIZING FACTORS WHICH ACCOUNT FOR THE A
C   AREA OF EACH SOURCE SECTOR.
C
C
      COMMON /A/ WV,RH,RL,D(3)
      COMMON /B/ PGAP(3,9), PHIT(3,9),PGAP2(3,9), PHIT2(3,9),STEF
      COMMON/C/COSTA(9,9,18),EMISSV(4),ABSORB(3), ESKY, EGRD, SECTAR(9)
      COMMON/D/CONT(3,5,9),C(3,5,9), SUMT(3,9), KELV, GT, NUSIM, ITIME
      COMMON/E/AT,THETA(9),PHI(18),XLF(9), YLF(9), ZLF(9), XS(9,18)
      COMMON/F/YS(9,18),ZS(9), CEDTR, B, FREQD(9,3) , WA(15),EPS
      COMMON/G/NSIG,N, ITMAX
      BANDW= 10.*CEDTR
       ALPHA2= 0.
      SINA2=0.
      DO 2 I=1,9
      SINA1=SINA2
      ALPHA2= ALPHA2 + BANDW
      SINA2= SIN (ALPHA2)
C
C... NOTE WE MUST DIVIDE BY SIN(THETA) SINCE WE ARE INTERESTED IN THE FLUX
C    BEFORE IT HITS A HORIZONTAL PANAL.
C
      SECTAR(I)= (SINA2**2-SINA1**2)/(18.*SIN(THETA(I)))
    2 CONTINUE
      RETURN
      END
       SUBROUTINE SET02(A,I,J)
C
C
C...SUBROUTINE SET02 SETS ALL ELEMENTS OF A 2-DIMENSIONAL ARRAY TO 0.0
C
C
       DIMENSION A(I,J)
      DO 10 K=1,I
      DO 10 L=1,J
      A(K,L)= 0.0
   10 CONTINUE
      RETURN
      END
      SUBROUTINE SET03 (A,I,J,K)
C
C
C...SUBROUTINE SET03 SETS ALL ELEMENTS  OF A  3-DIMENSIONAL ARRAY TO 0.0
C
```

```
C
       DIMENSION A(I,J,K)
      DO 10 L=1,I
      DO 10 M=1,J
      DO 10 N=1,K
      A(L,M,N)= 0.0
   10 CONTINUE
      RETURN
      END
      SUBROUTINE WMAT(TITLE)
      COMMON/B/ PGAP(3,9), PHIT(3,9), PGAP2(3,9), PHIT2(3,9),STEF
      DIMENSION W(4,9),TITLE(8)
C   WMAT CALCULATES THE W MATRIX.
C
      DO 10 M = 1,9
      W(1,M) = PHIT(1,M)
      W(2,M) = PGAP(1,M)-PGAP(1,M)*PGAP(2,M)
      W(3,M) = PGAP(1,M)*PGAP(2,M)-PGAP(1,M)*PGAP(2,M)*PGAP(3,M)
      W(4,M) = PGAP(1,M)*PGAP(2,M)*PGAP(3,M)
   10 CONTINUE
      WRITE(6,199)(TITLE(N),N=1,8)
      WRITE(3,199)(TITLE(N),N=1,8)
  199 FORMAT(* THE W AND S MATRICES FOR */8A10)
      WRITE(3,300)((W(M,N),N=1,9),M=1,4)
      WRITE(6,300)((W(M,N),N=1,9),M=1,4)
  300  FORMAT(9F7.4)
      RETURN
      END
```

SENSIT

```
      PROGRAM SENSIT(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE1,TAPE2)
C
      COMMON/PARA1/SIG,STA(3),S(3,3),STG(3),X(3),PARAM(16),A(3),
     1ALP(3),FMU,TA,TAC,TG,EPS(3),EPSTG,RH,RL
      COMMON/PARA2/BTA,BTG,BX(3),DBX(3),QX(3),DQX(3),RX(3),DRX(3)
      COMMON/ESTIM/FX(3),DFX(3,3)
      DIMENSION PAR(16),DSTEP(16),DP(16),DX(3),TEMP(3),XO(3),XX(3),
     1FSEN(3),PARMAX(16)
C
C ---   DEFINE INPUT VARIABLES   ---
C
      SIG=5.6686E-8
      STA(1)=0.6107
      STA(2)=0.1887
      STA(3)=0.0728
      STG(1)=0.0815
      STG(2)=0.2482
      STG(3)=0.7257
      S(1,1)=0.7715  $  S(1,2)=0.4769  $  S(1,3)=0.0523
      S(2,1)=0.2277  $  S(2,2)=1.1600  $  S(2,3)=0.1682
      S(3,1)=0.0830  $  S(3,2)=0.5698  $  S(3,3)=0.5414
C
C  ---   DEFINE NOMINAL VALUES FOR MODEL PARAMETERS   ---
C
      PAR(1)=ALP(1)=1.0
      PAR(2)=ALP(2)=1.0
      PAR(3)=ALP(3)=1.0
      PAR(4)=FMU=10.0
      PAR(5)=TA=14.6
      PAR(6)=TAC=14.6
      PAR(7)=TG=11.7
      PAR(8)=EPS(1)=1.0
      PAR(9)=EPS(2)=1.0
      PAR(10)=EPS(3)=1.0
      PAR(11)=EPSTG=1.0
      PAR(12)=RH=0.20
      PAR(13)=RL=0.66
      PAR(14)=A(1)=144.
      PAR(15)=A(2)=49.
      PAR(16)=A(3)=46.
C
C  ---   DEFINE INITIAL VALUES FOR STATE VARIABLES   ---
C
      XO(1)=20.4
      XO(2)=16.6
```

```
      XO(3)=16.3
C
C  ---   DEFINE UPPER BOUNDS FOR MODEL PARAMETERS   ---
C
      PARMAX(1)=PARMAX(2)=PARMAX(3)=1.0
      PARMAX(8)=PARMAX(9)=PARMAX(10)=PARMAX(11)=1.0
      PARMAX(4)=20.0
      PARMAX(5)=PARMAX(6)=PARMAX(7)=30.0
      PARMAX(12)=0.50
      PARMAX(13)=1.20
      PARMAX(14)=150.0
      PARMAX(15)=PARMAX(16)=60.
C
C  ---   DEFINE STEP-SIZES OF MODEL PARAMETERS FOR SENSITIVITY ANALYSIS   ---
C
      DSTEP(1)=DSTEP(2)=DSTEP(3)=DSTEP(8)=DSTEP(9)=DSTEP(10)=DSTEP(11)=
     1-0.005
       DSTEP(4)=-1.0
      DSTEP(5)=DSTEP(6)=DSTEP(7)=-1.0
      DSTEP(12)=-0.05
      DSTEP(13)=-0.05
      DSTEP(14)=-7.5
      DSTEP(15)=DSTEP(16)=-3.0
C
C  ---   START SENSITIVITY ANALYSIS   ---
C
      TOL=0.0001
      DO 100 IP=1,16
      DO 92 I=1,16
   92 PARAM(I)=PAR(I)
      DO 94 I=1,3
      XX(I)=XO(I)
   94 X(I)=XO(I)
      DO 90 NTIME=1,20
      FACTOR=NTIME-1
      DP(IP)=FACTOR*DSTEP(IP)
      PARAM(IP)=PARMAX(IP)+DP(IP)
   50 CALL FEVAL
C       WRITE(6,1010)(FX(I),I=1,3)
C1010     FORMAT(1H ,3F10.5)
      DO 20 I=1,3
   20 FX(I)=-FX(I)
      CALL SOLVE(FX,3,DFX,3,DX)
      DO 30 I=1,3
C       WRITE(6,1010) X(I),DX(I)
```

AD-A106 422 COLORADO STATE UNIV FORT COLLINS DEPT OF FOREST AND --ETC F/G 17/5
THERMAL VEGETATION CANOPY MODEL STUDIES.(U)
AUG 81 J A SMITH, K J RANSON, D NGUYEN DACW39-77-C-0073
UNCLASSIFIED WES/TR/EL-81-6 NL

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```
   30 X(I)=X(I)+DX(I)
      DO 40 I=1,3
      DEV=DX(I)
      IF(ABS(DEV) .GT. TOL) GO TO 50
      FSEN(I)=(X(I)-XX(I))/DSTEP(IP)
      XX(I)=X(I)
   40 TEMP(I)=X(I)
      WRITE(1,80) (TEMP(I),I=1,3),PARAM(IP)
   80 FORMAT(3F10.5)
   90 CONTINUE
  100 CONTINUE
      ENDFILE 1
      REWIND 1
      STOP
      END
      SUBROUTINE FEVAL
C
      COMMON/PARA1/SIG,STA(3),S(3,3),STG(3),X(3),PARAM(16),A(3),
     1ALP(3),FMU,TA,TAC,TG,EPS(3),EPSTG,RH,RL
      COMMON/PARA2/BTA,BTG,BX(3),DBX(3),QX(3),DQX(3),RX(3),DRX(3)
      COMMON/ESTIM/FX(3),DFX(3,3)
C
      ALP(1)=PARAM(1)
      ALP(2)=PARAM(2)
      ALP(3)=PARAM(3)
      FMU=PARAM(4)
      TA=PARAM(5)
      TAC=PARAM(6)
      TG=PARAM(7)
      EPS(1)=PARAM(8)
      EPS(2)=PARAM(9)
      EPS(3)=PARAM(10)
      EPSTG=PARAM(11)
      RH=PARAM(12)
      RL=PARAM(13)
      A(1)=PARAM(14)
      A(2)=PARAM(15)
      A(3)=PARAM(16)
      CALL FBTA(TA,BTA)
      CALL BFUNC(EPSTG,TG,BTG,DBTG)
      DO 10 I=1,3
      CALL BFUNC(EPS(I),X(I),BX(I),DBX(I))
      CALL QFUNC(X(I),TAC,FMU,QX(I),DQX(I))
      CALL RFUNC(X(I),TAC,FMU,RL,RH,RX(I),DRX(I))
   10 CONTINUE
```

```
      DO 20 IL=1,3
   20 FX(IL)=0.5*ALP(IL)*SIG*(BTA*STA(IL)+BX(1)*S(IL,1)+BX(2)*
     1S(IL,2)+BX(3)*S(IL,3)+BTG*STG(IL))+A(IL)-SIG*BX(IL)+QX(IL)
     2+RX(IL)
      DO 30 I=1,3
      DO 30 J=1,3
   30 DFX(I,J)=0.
      DO 40 IL=1,3
      DO 40 J=1,3
      IF(J.NE.IL) GO TO 35
      DFX(IL,J)=0.5*ALP(IL)*SIG*DBX(J)*S(IL,J)-SIG*DBX(IL)+DQX(IL)+
     1DRX(IL)
      GO TO 40
   35 DFX(IL,J)=0.5*ALP(IL)*SIG*DBX(J)*S(IL,J)
   40 CONTINUE
      RETURN
      END
      SUBROUTINE BFUNC(EPSI,XI,BXI,DBXI)
C
      BXI=EPSI*(XI+273.0)**4.
      DBXI=4.*EPSI*(XI+273.0)**3.
      RETURN
      END
      SUBROUTINE FBTA(TA,BTA)
C
      EPSTA=1.-0.261*EXP(-7.77E-4*TA*TA)
      CALL BFUNC(EPSTA,TA,BTA,DBTA)
      RETURN
      END
      SUBROUTINE QFUNC(XI,TAC,FMU,QXI,DQXI)
C
      IF(FMU.GT.30.) GO TO 10
      HC=0.69775*(20.4+0.2*FMU**.97)
      GO TO 20
   10 HC=0.69775*(0.95*FMU**.97)
   20 QXI=(XI-TAC)*HC*(-1.0)
      DQXI=HC*(-1.0)
      RETURN
      END
      SUBROUTINE RFUNC(XI,TAC,FMU,RL,RH,RXI,DRXI)
C
      RNUM=FEX(XI)*1.0E-6-RH*FEX(TAC)*1.0E-6
      RDEN=RL+(1./60.)*(0.04+1.27*FMU**(-0.5))
      RXI1=-697.75*(-0.566*XI+597.3)
      RXI2=RNUM/RDEN
      RXI=RXI1*RXI2
      DRXI=697.75*0.566*RXI2+RXI1*(0.056715E-6*FEX(XI))/RDEN
      RETURN
      END
```

```
      SUBROUTINE INVERSE(A,N,D)
C
C  ---   INVERT A 3*3 REAL MATRIX A WHOSE DETERMINANT IS D
C        THE RESULT WILL BE STORED IN A
C
      DIMENSION A(3,3),B(3,3)
C
      D=A(1,1)*A(2,2)*A(3,3)+A(1,2)*A(2,3)*A(3,1)+A(1,3)*A(2,1)*
     1A(3,2)-A(3,1)*A(2,2)*A(1,3)-A(1,1)*A(3,2)*A(2,3)-A(2,1)*
     2A(1,2)*A(3,3)
      B(1,1)=(A(2,2)*A(3,3)-A(2,3)*A(3,2))/D
      B(1,2)=-(A(2,1)*A(3,3)-A(2,3)*A(3,1))/D
      B(1,3)=(A(2,1)*A(3,2)-A(2,2)*A(3,1))/D
      B(2,1)=-(A(1,2)*A(3,3)-A(1,3)*A(3,2))/D
      B(2,2)=(A(1,1)*A(3,3)-A(1,3)*A(3,1))/D
      B(2,3)=-(A(1,1)*A(3,2)-A(1,2)*A(3,1))/D
      B(3,1)=(A(1,2)*A(2,3)-A(1,3)*A(2,2))/D
      B(3,2)=-(A(1,1)*A(2,3)-A(1,3)*A(2,1))/D
      B(3,3)=(A(1,1)*A(2,2)-A(1,2)*A(2,1))/D
      DO 10 I=1,3
      DO 10 J=1,3
   10 A(I,J)=B(I,J)
      RETURN
      END
      FUNCTION FEX(XI)
C
      XX=5.2342*EXP(0.056715*XI)
      FEX=XX
      RETURN
      END
      SUBROUTINE SOLVE(Y,N,A,M,X)
C
C     DIMENSION Y(N),A(N,M),X(M),ATA(M,M),ATY(M)
      DIMENSION Y(3),A(3,3),X(3),ATA(3,3),ATY(3)
C
      DO 10 I=1,M
      DO 10 J=1,M
      ATA(I,J)=0.
      DO 10 K=1,N
   10 ATA(I,J)=ATA(I,J)+A(K,I)*A(K,J)
      CALL INVERSE(ATA,M,D)
      DO 20 I=1,M
      ATY(I)=0.
      DO 20 J=1,N
   20 ATY(I)=ATY(I)+A(J,I)*Y(J)
```

```
      DO 30 I=1,M
      X(I)=0.
      DO 30 J=1,M
   30 X(I)=X(I)+ATA(I,J)*ATY(J)
      RETURN
      END
```

```
*DECK SRVC
      PROGRAM SRVC(INPUT,OUTPUT,TAPE6=OUTPUT,TAPE5=INPUT)
C.... SOLAR RADIATION - VEGETATION CANOPY REFLECTANCE MODEL             SRVC
C.... THIS PROGRAM CALCULATES THE APPARENT DIRECTIONAL REFLECTANCE OF A SRVC
C.... VEGETATION CANOPY AS A FUNCTION OF CANOPY GEOMETRY, LEAF REFLEC-  SRVC
C.... TANCE AND TRANSMISSION, SOIL REFLECTANCE, AND CANOPY IRRADIANCE   SRVC
C.... FOR A GIVEN SOLAR POSITION.                                       SRVC
C.... R.E. OLIVER AND J.A. SMITH  COLORADO STATE UNIVERSITY  JUNE, 1974 SRVC
C                                                                       SRVC
C.................... COMMON BLOCKS AND REFERENCES ..................... SRVC
C                                                                       SRVC
C    LABEL    EXTERNAL REFERENCES                                       SRVC
C                                                                       SRVC
C     C1       BLOCK DATA, LAMBTN, SUN, ETHRES, LANGLE, NRM, SETZ, UTIL, SRVC
C              AND COP.                                                 SRVC
C                                                                       SRVC
C     C2       LAMBTN, PDENS, AND OPTICAL.                              SRVC
C                                                                       SRVC
C     C4       LANGLE, PDENS, AND PGAP.                                 SRVC
C                                                                       SRVC
C     C6       ETHRES, SETZ, AND LAMBTN.                                SRVC
C                                                                       SRVC
C     C8       LANGLE.                                                  SRVC
C                                                                       SRVC
C     L1       OPTICAL.                                                 SRVC
C                                                                       SRVC
C     CMAT     PGAP AND LAMBTN                                          SRVC
C                                                                       SRVC
C     //       LANGLE AND LAMBTN.                                       SRVC
C                                                                       SRVC
      COMMON/C1/DAY,YEAR,TIME,GLAT,GLONG,DEC,BANDW,NLAM,THETS1,THETS2,  SRVC
     1NMAT,EXTRA(4),NOP,INIT,DUM1(13),                                  SRVC
     2CEDTR,CERTD,CEMTR,CEPIO2,CE1PI,CE2PI,DUM2(14),                    SRVC
     3SINLAT,COSLAT,SINDEC,COSDEC,COSH,SINZ,COSZ,SINAZ,COSAZ,LXS,LYS,LZS SRVC
      COMMON/C2/CANRM(17),SKYIM(17),DIFIM(17),R(17),T(17),RG(17),XLAM(17
     1),SOURCE(10,17),THETA(10),ZENITH(10)
      COMMON/C4/NANGLE(3,3),FLA(3,3,10),SLAI(3,3),FLAI(3,3),PHIT(3,3,10) SRVC
      COMMON/C6/DR(4,10,17),UR(4,10,17),THRESD(10),IGOD(4,10),IGOU(4,10) SRVC
     1,THRESU(10)                                                       SRVC
      COMMON /KIM/ INL(3,3,2)
      COMMON/C8/SINL,COSL,SINP,COSP                                     SRVC
      COMMON/L1/DATAID(7,9),XMU(17,9),C(17,17,9),NVEC(9)                SRVC
      COMMON/CMAT/MTP(3),NLAY,OPM(10)                                   SRVC
     A,ENDLC                                                            SRVC
      COMMON AVEC(17),XK(9),SXL,SYL,SZL,XLF,YLF,ZLF                     SRVC
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      1,XS(10,18),YS(10,18),ZS(10)                                        SRVC
      A,ENDB3                                                             SRVC
       COMMON /AB3/TABSO(4,17)
C.......................... INTERNAL ARRAYS .......................... SRVC
       DIMENSION JOBID(8),VECT(17),SIG(17),V(17,17),COR(17,17)            SRVC
       DIMENSION COV(10,17,17),COVM(17,17)                                SRVC
       DIMENSION XLFA(19),YLFA(19),DM(17),DM1(17),REFER(17)               SRVC
       DIMENSION RIT(10,17),RITBAR(10,17),RBAR(10,17)                     SRVC
       DIMENSION F(19),OP(9)                                              SRVC
       INTEGER RORT
       REAL LXS,LYS,LZS,INCLF                                             SRVC
       INTEGER DAY,YEAR,TH,TM,ZDEG                                        SRVC
 8000  CONTINUE
       DO 10  I=1,10
       THETA(I)=0.
       ZENITH(I)=0.
       ZS(I)=0.
       THRESD(I)=0.
       OPM(I)=0.
       THRESU(I)=0.
       DO 10  J=1,18
   10  YS(I,J)=0.
       DO 4  K=1,17
       CANRM(K)=0.
       SKYIM(K)=0.
       DIFIM(K)=0.
       R(K)=0.
       T(K)=0.
       RG(K)=0.
       DM(K)=0.
       DM1(K)=0.
       SIG(K)=0.
       XLAM(K)=0.
       DO 4  I=1,10
       SOURCE(I,K)=0.
       RIT(I,K)=0.
       RITBAR(I,K)=0.
       RBAR(I,K)=0.
    4  CONTINUE
       DO 9  I=1,19
       F(I)=0.
       XLFA(I)=0.
    9  YLFA(I)=0.
       DO 12  I=1,9
       NVEC(I)=0.
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      OP(I)=0.
      XK(I)=0.
      DO 12  J=1,17
   12 XNU(J,I)=0.
      DO 7  I=1,3
      NTP(I)=0.
      DO 7  J=1,3
      NANGLE(I,J)=0.
      SLAI(I,J)=0.
      FLAI(I,J)=0.
      DO 7  K=1,10
      FLA(I,J,K)=0.
    7 PHIT(I,J,K)=0.
      DO 6  I=1,3
      DO 6  J=1,3
      DO 6  K=1,2
    6 INL(I,J,K)=0.
C....PERIPHERAL CONTROLS                                                 SRVC
      IHIST = 0                                                         SRVC
      ISTOH = 1                                                         SRVC
      IFILE = 5                                                         SRVC
C....IFILE ASSIGNMENT COULD BE MADE THRU A READ STATEMENT.
      IF(EOF(5).NE.0.) STOP                                             SRVC
      IF(IHIST.EQ.1) CALL FUN(-1,-1)                                    SRVC
C....GENERAL SIMULATION CONSTRAINTS                                      SRVC
      READ(IFILE,100) JOBID,DAY,YEAR,TH,TM,GLAT,GLONG,DEC,NBANDS,       SRVC
     1NLAM,NMAT,INIT,NSAMP,NTRIAL                                       SRVC
      IF(EOF(5).NE.0.) STOP                                             SRVC
      READ(IFILE,102) NLAY                                              SRVC
      BANDW=90/NBANDS                                                   SRVC
      WRITE(6,200) JOBID,DAY,YEAR,TH,TM,GLAT,GLONG,DEC,BANDW,NLAM,NMAT, SRVC
     1INIT,NSAMP,NTRIAL,NLAY                                            SRVC
      READ(IFILE,101) THRESD $READ(IFILE,101) THRESU                    SRVC
      WRITE(6,221) THRESD,THRESU                                        SRVC
C....PARAMETER INITIALIZATION AND CONVERSION                             SRVC
      DO 1073 J=1,4
      DO 1073 I=1,NLAM
      TABSO(J,I)=0.0
 1073 CONTINUE
      NSOUR=NBANDS+1                                                    SRVC
      NLAYP1=NLAY+1                                                     SRVC
      CALL RANSET(INIT)                                                 SRVC
      XT1=TH                                                            SRVC
      XT2=TM                                                            SRVC
      TIME=XT1+(XT2/60.)                                                SRVC
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      GLAT=GLAT*CEDTR                                                   SRVC
      GLONG=GLONG*CEDTR                                                 SRVC
      DEC=DEC*CEDTR                                                     SRVC
      BANDW=BANDW*CEDTR                                                 SRVC
C....SUN POSITION PARAMETERS                                            SRVC
      CALL SUN                                                          SRVC
      WRITE(6,222) LXS,LYS,LZS                                          SRVC
      ZS(1) = LZS                                                       SRVC
C....COEFFICIENTS FOR DIFFUSE RADIATION VECTORS                         SRVC
C....SENSOR/BAND AREA RATIO FOR ALL DIFFUSE BANDS                       SRVC
      ALPHA2=0.                                                         SRVC
      SINA2=0.                                                          SRVC
      DO 2 I=1,NBANDS                                                   SRVC
      SINA1=SINA2                                                       SRVC
      ALPHA2=ALPHA2+BANDW                                               SRVC
      SINA2=SIN(ALPHA2)                                                 SRVC
      XK(I)=SINA2*SINA2-SINA1*SINA1                                     SRVC
    2 CONTINUE
      WRITE(6,208) (XK(I),I=1,NBANDS)                                   SRVC
C....SOURCE DIRECTION INCLINATION ANGLES                                SRVC
      TOTAL=0.                                                          SRVC
      THETA(1)=(BANDW/2.)-BANDW                                         SRVC
      DO 3 I=1,NBANDS                                                   SRVC
      THETA(I+1)=THETA(I)+BANDW                                         SRVC
    3 CONTINUE
      THETA(1)=CEPIO2-ACOS(COSZ)                                        SRVC
      CONS=LZS*TOTAL                                                    SRVC
      DO 50 I=1,10                                                      SRVC
   50 ZENITH(I)=CEPIO2-THETA(I)                                         SRVC
      WRITE(6,223) THETA                                                SRVC
C....DIRECTION COSINES OF AZIMUTHAL SECTORS IN THE DIFFUSE BANDS        SRVC
      DEG20=20.*CEDTR                                                   SRVC
      DO 60 JSOR=2,NSOUR                                                SRVC
      ZS(JSOR)=SIN(THETA(JSOR))                                         SRVC
      PHI=10.*CEDTR                                                     SRVC
      DO 60 IPHI=1,18                                                   SRVC
      XS(JSOR,IPHI)=COS(THETA(JSOR))*COS(PHI)                           SRVC
      YS(JSOR,IPHI)=COS(THETA(JSOR))*SIN(PHI)                           SRVC
   60 PHI=PHI+DEG20                                                     SRVC
C....CANOPY GEOMETRY.  EACH CANOPY LAYER IS COMPOSED OF ONE OPTICAL     SRVC
C....MATERIAL WHICH MAY BE SPECIFIED AND UNIQUE GEOMETRICAL PROPERTIES. SRVC
C....CANOPY GEOMETRIC PARAMETERS CONSIST OF (1)LEAF ANGLE FREQUENCY     SRVC
C....DISTRIBUTION FUNCTION DENOTED BY XLFA AND YLFA (2)LEAF AREA INDEX  SRVC
C....DENOTED BY FLAI AND (3)CANOPY DENSITY DENOTED BY SLAI.  XLFA (DEG) SRVC
C....AND YLFA MUST BE SPECIFIED AT AN ODD NUMBER (NANG) OF EVENLY SPACED SRVC
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C....POINTS.  FLAI IS NON-NEGATIVE AND SLAI RANGES BETWEEN 0 AND 1.     SRVC
      DELF=10.*CEDTR                                                    SRVC
      WRITE(6,227)                                                      SRVC
      DO 350 IL=1,NLAY                                                  SRVC
      READ(IFILE,102) NANG                                              SRVC
C...READ IN THE NUMBER OF MATERIALS IN ANY GIVEN LAYER
      READ(IFILE,102) IMAT                                              SRVC
      MTP(IL) = IMAT                                                    SRVC
      IMAT1=IMAT
      DO 351 J=1,IMAT1
      IMAT = J
      READ(IFILE,101) (XLFA(I),YLFA(I),I=1,NANG)                        SRVC
      READ(IFILE,101) SLAI(IL,IMAT),FLAI(IL,IMAT)                       SRVC
C....INTEGRATE AND NORMALIZE THE LEAF ANGLE FREQUENCY DISTRIBUTION       SRVC
C....FUNCTION USING SIMPSONS RULE--THIS IS TEMPORARILY DENOTED BY F.     SRVC
C....M-1 EQUALLY SPACED INTERVALS OF F ARE THEN DETERMINED AND DENOTED   SRVC
C....BY FLA (M POINTS).  THE TABLE FLA IS USED FOR RANDOMLY SELECTING    SRVC
C....LEAF INCLINATION ANGLES.                                            SRVC
      DO 305 I=1,NANG                                                   SRVC
305   XLFA(I)=XLFA(I)*CEDTR                                             SRVC
      M=((NANG-1)/2)+1                                                  SRVC
      NANGLE(IL,IMAT)=M                                                 SRVC
      CALL TBLR(M,XLFA,YLFA,DM,F)                                       SRVC
      WRITE(6,233) (F(I),I=1,M)                                         SRVC
      DO 310 IANG=1,M                                                   SRVC
  310 FLA(IL,IMAT,IANG)=DM(IANG)                                        SRVC
C....NORMALIZE THE INPUT LEAF FREQUENCY DISTRIBUTION FUNCTION TO OBTAIN  SRVC
C....A DENSITY FUNCTION F WHICH IS SPECIFIED AT M POINTS.                SRVC
      FTOT=0.                                                           SRVC
      DO 311 I=1,NANG                                                   SRVC
  311 FTOT=FTOT+YLFA(I)                                                 SRVC
      DO 312 I=1,9                                                      SRVC
  312 F(I)=(YLFA(2*I)+YLFA(2*I+1))/FTOT                                 SRVC
      DO 315 I=1,NANG                                                   SRVC
315   XLFA(I)=XLFA(I)*CERTD                                             SRVC
      WRITE(6,230) IL,IMAT,NANG,(XLFA(I),YLFA(I),I=1,NANG)              SRVC
      WRITE(6,231) NANGLE(IL,IMAT)                                      SRVC
      WRITE(6,232) (FLA(IL,IMAT,I),I=1,M)                               SRVC
      M=M-1                                                             SRVC
      WRITE(6,233) (F(I),I=1,M)                                         SRVC
      WRITE(6,207) FLAI(IL,IMAT),SLAI(IL,IMAT)                          SRVC
C....CALCULATE THE MEAN PROJECTION (OP) IN THE DIRECTION OF THE SOURCE   SRVC
C...(THETA) OF ONE UNIT LEAF AREA WITH INCLINATION INCLF.  THE LEAVES    SRVC
C....AT THIS ANGLE ARE ASSUMED TO BE AZIMUTHALLY ISOTROPIC.              SRVC
      DO 330 IANGLE=1,NSOUR                                             SRVC
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      INCLF=-5.*CEDTR                                                   SRVC
      DO 320 I=1,9                                                      SRVC
      INCLF=INCLF+DELF                                                  SRVC
  320 CALL COP(INCLF,THETA(IANGLE),OP(I))                               SRVC
C....CALCULATE THE MEAN PROJECTION (OPM) IN THE DIRECTION OF THE SOURCE SRVC
C....(THETA) OF ONE UNIT LEAF AREA AVERAGED OVER THE CANOPY LEAF ANGLE  SRVC
C....DENSITY FUNCTION F.                                                SRVC
      CALL COPM(F,OP,OPM(IANGLE))                                       SRVC
C....CALCULATE THE PROBABILITY OF A HIT (PHIT) FOR A LIGHT RAY WITH     SRVC
C....SOURCE DIRECTION THETA.                                            SRVC
      CALL PDENS(IL,IMAT,IANGLE,OPM(IANGLE))                            SRVC
      WRITE(6,235) OP,OPM(IANGLE),PHIT(IL,IMAT,IANGLE)                  SRVC
  330 CONTINUE                                                          SRVC
  351 CONTINUE
  350 CONTINUE                                                          SRVC
      WRITE(6,228)                                                      SRVC
C....REFLECTANCE AND TRANSMISSION VECTORS ARE READ FOR EACH CANOPY      SRVC
C....CONSTITUENT.  IN ADDITION REFLECTANCE VECTORS ARE READ FOR THE SOIL SRVC
C....BACKGROUND AND THE MEASURED CANOPY.  THE MEAN VECTOR AND COVARIANCE SRVC
C....AND CORRELATION MATRICES ARE CALCULATED AS WELL AS THE SQUARE-ROOT SRVC
C....MATRIX WHICH IS SUBSEQUENTLY USED FOR MULTIVARIATE NORMAL          SRVC
C....STOCHASTIC VECTOR SAMPLING.                                        SRVC
C                                                                       SRVC
C....WAVELENGTHS TO BE SIMULATED                                        SRVC
      READ(IFILE,101) (XLAM(I),I=1,NLAM)                                SRVC
      WRITE(6,201) (XLAM(I),I=1,NLAM)                                   SRVC
C....CONSTITUENT OPTICAL VECTORS                                        SRVC
C...READ NUMBER OF CONSTITUENT OPTICAL VECTORS WHICH EQUALS 2*NTYPE
C   * NUMBER OF LAYERS
      READ (IFILE,105) NOP
  105 FORMAT (I10)
      READ(IFILE,104)(DATAID(I),I=1,7)
      WRITE(6,5) (DATAID(I),I=1,7)
      READ(IFILE,101) (CANRM(J),J=1,NLAM)
      WRITE(6,294)
      WRITE(6,203) (CANRM(J),J=1,NLAM)
      READ(IFILE,101) (SKYIM(J),J=1,NLAM)
      WRITE(6,295)
      WRITE(6,203) (SKYIM(J),J=1,NLAM)
      READ(IFILE,101) (DIFIM(J),J=1,NLAM)
      WRITE(6,296)
      WRITE(6,203) (DIFIM(J),J=1,NLAM)
      READ(IFILE,101) (RG(J),J=1,NLAM)
      WRITE(6,297)
      WRITE(6,203) (RG(J),J=1,NLAM)
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      DO 11  NL=1,NOP
      READ(IFILE,106) NULAY,MTYP,RORT,(DATAID(I),I=1,7)
      WRITE(6,202)(DATAID(I),I=1,7),NULAY,MTYP,RORT
      READ(IFILE,101) (XMU(I,NL),I=1,NLAM)
      INL(NULAY,MTYP,RORT)=NL
      WRITE(6,204) (XMU(I,NL),I=1,NLAM)
   11 CONTINUE                                                          SRVC
      WRITE (6,210)                                                     SRVC
C.....................          BIG LOOP          ...................... SRVC
      ISTOP=0                                                           SRVC
      DO 40  J=1,NLAM
      SOURCE(1,J)=(SKYIM(J)-DIFIM(J))/(SKYIM(J))
      DO 40  I=1,NBANDS
   40 SOURCE(I+1,J)=(DIFIM(J)*XK(I))/(SKYIM(J))
      WRITE(6,209)
      DO 45  I=1,NSOUR
   45 WRITE(6,203) (SOURCE(I,J),J=1,NLAM)
      DO 7000 ISAMP=1,NSAMP                                             SRVC
      DO 6000 ITRIAL=1,NTRIAL                                           SRVC
C....COMPUTE PROPORTION OF IRRADIANCE WHICH IS DIRECT AND PROPORTION    SRVC
C....WHICH IS DIFFUSE.                                                  SRVC
C....POPULATE FIRST (TOP) DOWN DWELL LAYER (DR) WITH INCIDENT DIRECT AND SRVC
C....DIFFUSE LIGHT.  DOWN DWELL RADIATION FLUX (DR) IS INDEXED FROM 1 TO SRVC
C....NLAY IN A DOWN GOING SEQUENCE.  UPWARD DWELL RADIATION FLUX (UR)   SRVC
C....IS INDEXED FROM 1 TO NLAY+1 IN UPWARD GOING SEQUENCE.  THAT IS FOR SRVC
C....FOR UR, LAYER 1 IS THE LAYER IMMEDIATELY ABOVE THE BACKGROUND.  THE SRVC
C....FLUX IN LAYER NLAY+1 IS THAT WHICH ESCAPES THE CANOPY AND TOGETHER  SRVC
C....WITH THE INCIDENT FLUX DETERMINES THE CANOPY REFLECTANCE.           SRVC
      DO 8  K=1,17
      DO 8  J=1,10
      DO 8  I=1,4
      UR(I,J,K)=0.
      DR(I,J,K)=0.
      IGOD(I,J)=0.
      IGOU(I,J)=0.
    8 CONTINUE
      DO 1003 J=1,NSOUR                                                 SRVC
      DO 1003 K=1,NLAM                                                  SRVC
 1003 DR(1,J,K)=SOURCE(J,K)                                             SRVC
C....SET FLUX LEVEL INDICATORS (DOWNWARD)                               SRVC
      CALL ETHRES(NLAY,NSOUR,-1)                                        SRVC
C...........FAST LOOP TRACES LIGHT ATTENUATION THROUGH CANOPY........... SRVC
C....FLUX PASSING THROUGH LAYERS IN A DOWNWARD DIRECTION                SRVC
2000  CONTINUE                                                          SRVC
      DO 2600 IL=1,NLAY                                                 SRVC
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      DO 2500 JSOR=1,NSOUR                                          SRVC
C....CHECK FLUX LEVEL INDICATOR                                     SRVC
      IF(IGOD(IL,JSOR).EQ.0.) GO TO 2500                            SRVC
C....DID LIGHT STRIKE LEAF                                          SRVC
      CALL PGAP(IL,JSOR,-1,IHIT,MTYPE)                              SRVC
      IF(IHIT.EQ.0) GO TO 2200                                      SRVC
      DO 2100 IPHIP=1,18                                            SRVC
C....DIRECTION COSINES OF SOURCE SECTOR (LVLH)                      SRVC
      SXL = XS(JSOR,IPHIP)                                          SRVC
      SYL = YS(JSOR,IPHIP)                                          SRVC
      SZL = ZS(JSOR)                                                SRVC
      CALL LAMBTN(IL,JSOR,MTYPE,-1,NSOUR)                           SRVC
 2100 CONTINUE                                                      SRVC
      GO TO 2400                                                    SRVC
C....GAP ENCOUNTERED IN DOWNWARD PATH                               SRVC
 2200 DO 2250 KL=1,NLAM                                             SRVC
 2250 DR(IL+1,JSOR,KL)=DR(IL+1,JSOR,KL)+DR(IL,JSOR,KL)              SRVC
 2400 CALL SETZ(IL,JSOR,-1)                                         SRVC
2500  CONTINUE                                                      SRVC
      CALL ETHRES(NLAY,NSOUR,-1)                                    SRVC
 2600 CONTINUE                                                      SRVC
C....BACKGROUND REACHED - REFLECTS LAMBERTIAN                       SRVC
      DO 3600 JSOR=1,NSOUR                                          SRVC
      DO 3400 JJ=2,NSOUR                                            SRVC
      IL = NLAY + 1                                                 SRVC
      DO 3400 KL=1,NLAM                                             SRVC
      UR(1,JJ,KL)=UR(1,JJ,KL)+RG(KL)*DR(IL,JSOR,KL)*XK(JJ-1)
 3400 TABSO(4,KL)=TABSO(4,KL)+(1.-RG(KL))*DR(IL,JSOR,KL)*XK(JJ-1)
      CALL SETZ(NLAY+1,JSOR,-1)                                     SRVC
 3600 CONTINUE                                                      SRVC
      CALL ETHRES(NLAY,NSOUR,+1)                                    SRVC
C....FLUX PASSING THROUGH LAYERS IN AN UPWARD DIRECTION             SRVC
      DO 4600 IL=1,NLAY                                             SRVC
      DO 4500 JSOR=2,NSOUR                                          SRVC
C....CHECK FLUX LEVEL INDICATOR                                     SRVC
      IF(IGOU(IL,JSOR).EQ.0) GO TO 4500                             SRVC
C....DID LIGHT STRIKE LEAF                                          SRVC
      CALL PGAP(IL,JSOR,+1,IHIT,MTYPE)                              SRVC
      IF(IHIT.EQ.0) GO TO 4200                                      SRVC
      DO 4100 IPHIP=1,18                                            SRVC
C....DIRECTION COSINES OF SOURCE SECTOR (LVLH)                      SRVC
      SXL = XS(JSOR,IPHIP)                                          SRVC
      SYL = YS(JSOR,IPHIP)                                          SRVC
      SZL = ZS(JSOR)                                                SRVC
      CALL LAMBTN(IL,JSOR,MTYPE,+1,NSOUR)                           SRVC
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 4100 CONTINUE                                                          SRVC
      GO TO 4400                                                        SRVC
C....GAP ENCOUNTERED IN UPWARD PATH                                     SRVC
 4200 DO 4250 KL=1,NLAM                                                 SRVC
 4250 UR(IL+1,JSOR,KL)=UR(IL+1,JSOR,KL)+UR(IL,JSOR,KL)                  SRVC
 4400 CALL SETZ(IL,JSOR,+1)                                             SRVC
4500  CONTINUE                                                          SRVC
      CALL ETHRES(NLAY,NSOUR,+1)                                        SRVC
 4600 CONTINUE                                                          SRVC
      CALL ETHRES(NLAY,NSOUR,-1)                                        SRVC
      CALL ETHRES(NLAY,NSOUR,+1)                                        SRVC
C....RECYCLE THROUGH LAYERS UNTIL FLUX EXHAUSTED                        SRVC
      DO 5000 IL=1,NLAY                                                 SRVC
      DO 5000 JSOR=2,NSOUR                                              SRVC
      IF (IGOU(IL,JSOR).NE.0) GO TO 2000                                SRVC
5000  CONTINUE                                                          SRVC
      DO 5001 IL=2,NLAYP1                                               SRVC
      DO 5001 JSOR=1,NSOUR                                              SRVC
      IF(IGOD(IL,JSOR).NE.0) GO TO 2000                                 SRVC
 5001 CONTINUE                                                          SRVC
C....FLUX EXHAUSTED IN ALL SOURCES--COMPUTE REFLECTANCE FOR THIS TRIAL   SRVC
      DO 5200 JSOR=2,NSOUR                                              SRVC
      DO 5200 KL=1,NLAM                                                 SRVC
      RIT(JSOR,KL)=UR(NLAY+1,JSOR,KL)/XK(JSOR-1)
 5200 RITBAR(JSOR,KL)=RITBAR(JSOR,KL)+RIT(JSOR,KL)                      SRVC
      WRITE(6,283) ISAMP,ITRIAL
      DO 5300 JSOR=2,NSOUR                                              SRVC
      ZDEG=105-10*JSOR                                                  SRVC
 5300 WRITE(6,284) ZDEG,(RIT(JSOR,KL),KL=1,NLAM)                        SRVC
 6000 CONTINUE                                                          SRVC
C....TRIALS COMPLETE FOR THIS SAMPLE POINT                              SRVC
      FTRIAL=NTRIAL                                                     SRVC
 6200 DO 6300 JSOR=2,NSOUR                                              SRVC
      DO 6300 KL=1,NLAM                                                 SRVC
 6300 RITBAR(JSOR,KL)=RITBAR(JSOR,KL)/FTRIAL                            SRVC
      WRITE(6,286) ISAMP                                                SRVC
      DO 6400 JSOR=2,NSOUR                                              SRVC
      ZDEG=105-10*JSOR                                                  SRVC
 6400 WRITE(6,284) ZDEG,(RITBAR(JSOR,KL),KL=1,NLAM)                     SRVC
      DO 6600 JSOR=2,NSOUR                                              SRVC
      DO 6500 KL=1,NLAM                                                 SRVC
      RBAR(JSOR,KL)=RBAR(JSOR,KL)+RITBAR(JSOR,KL)                       SRVC
      DO 6500 KLL=1,NLAM                                                SRVC
 6500 COV(JSOR,KL,KLL)=COV(JSOR,KL,KLL)+RITBAR(JSOR,KL)*RITBAR(JSOR,KLL) SRVC
      DO 6600 KL=1,NLAM                                                 SRVC
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 6600 RITBAR(JSOR,KL)=0.                                                   SRVC
      IF(ISTOP.EQ.1) GO TO 7100                                            SRVC
 7000 CONTINUE                                                             SRVC
      FSAMP=NSAMP                                                          SRVC
      GO TO 7150                                                           SRVC
 7100 FSAMP=ISAMP                                                          SRVC
C....ALL SAMPLE POINTS ESTIMATED                                           SRVC
 7150 DO 7200 JSOR=2,NSOUR                                                 SRVC
      DO 7200 KL=1,NLAM                                                    SRVC
 7200 RBAR(JSOR,KL)=RBAR(JSOR,KL)/FSAMP                                    SRVC
      DO 7900 JSOR=2,NSOUR                                                 SRVC
      ZDEG=105-10*JSOR                                                     SRVC
      IF(FSAMP.LE.1.) GO TO 7600                                           SRVC
      DO 7400 I=1,NLAM                                                     SRVC
      DO 7300 J=1,NLAM                                                     SRVC
 7300 COV(JSOR,I,J)=(COV(JSOR,I,J)-FSAMP*RBAR(JSOR,I)*RBAR(JSOR,J))        SRVC
     1/(FSAMP-1.)                                                          SRVC
 7400 SIG(I)=SQRT(COV(JSOR,I,I))                                           SRVC
      DO 7500 I=1,NLAM                                                     SRVC
      DO 7500 J=1,NLAM                                                     SRVC
 7500 COR(I,J)=COV(JSOR,I,J)/(SIG(I)*SIG(J))                               SRVC
 7600 WRITE(6,287) ZDEG,(RBAR(JSOR,KL),KL=1,NLAM)                          SRVC
      WRITE(6,293) (SIG(KL),KL=1,NLAM)
      IF(FSAMP.LE.1.) GO TO 7900                                           SRVC
      WRITE(6,288)                                                         SRVC
      DO 7700 I=1,NLAM                                                     SRVC
 7700 WRITE(6,289) (COV(JSOR,I,J),J=1,NLAM)                                SRVC
      WRITE(6,291)                                                         SRVC
      DO 7800 I=1,NLAM                                                     SRVC
 7800 WRITE(6,289) (COR(I,J),J=1,NLAM)                                     SRVC
 7900 CONTINUE                                                             SRVC
      DO 7213 IK=1,4
      DO 7213 KL=1,NLAM
      TABSO (IK,KL)=TABSO(IK,KL)/(FSAMP*FTRIAL)
 7213 CONTINUE
      DO 7215 I=1,4
      JJ=I
      WRITE (6,7214) JJ,(TABSO(I,J),J=1,NLAM)
 7214 FORMAT ( * THE LAYER IS*,I2,* THE ABSORPTIONS ARE *,6(F8.5,1X))
 7215 CONTINUE
      IF(IFILE.EQ.5) GO TO 8000                                            SRVC
      STOP                                                                 SRVC
C.............................DATA FORMATS............................. SRVC
  100 FORMAT(8A10,/,4X,I3,7X,I4,7X,2I2,6X,F6.2,7X,F7.2,5X,F7.2,8X,I2,/,   SRVC
     15X,I2,7X,I1,7X,I5,9X,I5,8X,I5)                                       SRVC
```

```
101 FORMAT(8F10.5)                                                       SRVC
102 FORMAT(I10,7A10)                                                     SRVC
103 FORMAT(8E10.4)                                                       SRVC
104 FORMAT(7A10)
  5 FORMAT(*0*,7A10)
106 FORMAT(3I1,7A10)
200 FORMAT(*1*,43X,*SOLAR RADIATION/VEGETATION CANOPY REFLECTANCE MODE SRVC
   1L*,//,64X,*INPUT DATA*,//,1X,8A10,/,                                 SRVC
   2* JULIAN DAY *,I3,*, YEAR *,I4,*, TIME *,2I2,* HOURS*,/,             SRVC
   3* LATITUDE = *,F6.2,* DEGREES, LONGITUDE = *,F7.2,* DEGREES*,/,      SRVC
   4* SOLAR DECLINATION = *,F6.2,* DEGREES*,/,                           SRVC
   5* BAND WIDTH OF DIFFUSE VECTORS = *,F5.1,* DEGREES*,/,               SRVC
   6* NUMBER OF WAVELENGTH BANDS SIMULATED *,I2,/,                       SRVC
   7* NUMBER OF CANOPY CONSTITUENTS *,I1,/,                              SRVC
   8* K DIGIT ODD NO. TO INITIALIZE RANDOM SEQUENCE = *,I5,/,            SRVC
   9* NSAMP =*,I5,/,                                                     SRVC
   A* NTRIAL = *,I5,/,                                                   SRVC
   B* NLAY = *,I1,                                                       SRVC
   C)                                                                    SRVC
201 FORMAT(*0WAVELENGTHS SIMULATED*,/,*0*,F7.4,16F8.4)                   SRVC
202 FORMAT(*0*,7A10/* *,*NUMBER OF LAYERS =  *,I1/* *,
   1*MATERIAL TYPE =  *,I1/* *,*R OR T     *,I1)
203 FORMAT(* *,F7.4,16F8.4)                                              SRVC
204 FORMAT(*0      MEAN*,/,8X,10E12.4)                                   SRVC
205 FORMAT(*0      COVARIANCE MATRIX*)                                   SRVC
206 FORMAT(*0RANDOM VECTOR GENERATED FROM THE *,7A10,/,(* *,10E12.4))   SRVC
207 FORMAT(*0LAI = *,F4.2,4X,*S = *,F4.2)                               SRVC
208 FORMAT(*0DIFFUSE VECTOR COEFFICIENTS*,/,                             SRVC
   19(*      K  *),/,(9F8.4))                                            SRVC
209 FORMAT(*0IRRADIANCE SOURCE VECTORS*)                                 SRVC
210 FORMAT(1H1)                                                          SRVC
211 FORMAT(*0      CORRELATION MATRIX*)                                  SRVC
212 FORMAT(*0DM1 = *,9F8.4)                                              SRVC
221 FORMAT(*0THRESD = *,10F8.4/* THRESU = *,10F8.4)                      SRVC
222 FORMAT(*0DIRECTION COSINES OF SUN       *,3F8.4)                     SRVC
223 FORMAT(*0THETA =*,10F8.4)                                            SRVC
227 FORMAT(///* *,25(1H.),2X,*CANOPY GEOMETRY*,2X,25(1H.)//)             SRVC
228 FORMAT(/* *,25(1H.))                                                 SRVC
230 FORMAT(*0LEAF ANGLE COMPUTATIONS  -  IL = *,I1,                      SRVC
   1*  IMAT = *,I1,*  NANG = *,I2,/,* XLFA,YLFA*,                        SRVC
   1/,(2X,16F8.3))                                                       SRVC
231 FORMAT(*0NANGLE(IL,IMAT) = *,I2)                                     SRVC
232 FORMAT(*0     FLA =*,10F8.3)                                         SRVC
233 FORMAT(*0     F   =*,10F8.3)                                         SRVC
235 FORMAT(*0     OP  =*,9F8.3,3X,*OPM = *,F8.3,3X,*PHIT = *,F8.3)       SRVC
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251 FORMAT(8X,10E12.4)                                                  SRVC
282 FORMAT(*OREFER = *,8E13.4)                                          SRVC
283 FORMAT(*OREFLECTANCE FOR SAMPLE*,I3,* TRIAL*,I3,5X,                 SRVC
   1*COMPUTATION TIME WAS*,F5.1,* SECONDS.*)                            SRVC
284 FORMAT(* Z =*,I3,* DEG*,3X,10F7.3)                                  SRVC
285 FORMAT(*OCAUTION....SAMPLE*,I3,* CONTAINS ONLY*,I3,* TRIALS.*)      SRVC
286 FORMAT(*0*,75(1H.)/* MEAN REFLECTANCE FOR SAMPLE*,I3)               SRVC
287 FORMAT(*OGRAND MEAN FOR Z =*,I3,* DEGREES.*,3X,10F7.3)              SRVC
288 FORMAT(*0   COVARIANCE MATRIX*)                                     SRVC
289 FORMAT(7X,10F12.8)                                                  SRVC
291 FORMAT(*0   CORRELATION MATRIX*)                                    SRVC
292 FORMAT(1X,120(1H-))                                                 SRVC
293 FORMAT(*OSTDEV*,1X,10F12.8)
294 FORMAT(*OMEASURED REFLECTANCE*)
295 FORMAT(*OGLOBAL IRRADIANCE*)
296 FORMAT(*ODIFFUSE IRRADIANCE*)
297 FORMAT(*OSOIL REFLECTANCE*)
    END                                                                 SRVC
*DECK LAMBIN
      SUBROUTINE LAMBTN(IL,JSOR,MTYPE,IDIR,NSOUR)                       LAMBTN
C.....FOR A GIVEN FLUX SOURCE THIS PROGRAM CALLS THE APPROPRIATE         LAMBTN
C.....PROGRAMS TO DETERMINE LEAF ORIENTATION AND OPTICAL PROPERTIES      LAMBTN
C.....AND UPDATES THE DIFFUSE SOURCES WITH SCATTERED FLUX.               LAMBTN
C    SXL, SYL, SZL                                                      LAMBTN
C    JSOR                                                               LAMBTN
C    LXS, LYS, LZS                                                      LAMBTN
C    IDIR                                                               LAMBTN
C    NLAM                                                               LAMBTN
C    DR(I,J,K)                                                          LAMBTN
C    UR(I,J,K)                                                          LAMBTN
C    MTYPE                                                              LAMBTN
C    IL                                                                 LAMBTN
C    NSOUR                                                              LAMBTN
C    R,T
C    ZENITH                                                             LAMBTN
C  OUTPUT VARIABLES                                                     LAMBTN
C    DR(I,J,K)                                                          LAMBTN
C    UR(I,J,K)                                                          LAMBTN
C                                                                       LAMBTN
      COMMON DUM0(17),XK(9),SXL,SYL,SZL,XLF,YLF,ZLF                     LAMBTN
      COMMON/C1/DUM1(7),NLAM,DUM2(26),CE1PI,DUM3(24),LXS,LYS,LZS        LAMBTN
      COMMON/C2/DUM4(51),R(17),T(17),RG(17),DUM5(197),ZENITH(10)
      COMMON/C6/DR(4,10,17),UR(4,10,17)                                 LAMBTN
      COMMON/CMAT/MTP(3),NLAY,OPM(10)                                   LAMBTN
C
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      COMMON /AB3/TABSO(4,17)
      DIMENSION H(17),PTRP(2,17)
      REAL LXS,LYS,LZS                                                  LAMBTN
      DATA PIO2/1.570796327/                                            LAMBTN
C....SET DIRECTION COSINES OF SOURCE                                    LAMBTN
      XL=SXL                                                            LAMBTN
      YL=SYL                                                            LAMBTN
      ZL=SZL                                                            LAMBTN
      IF(JSOR.NE.1) GO TO 100                                           LAMBTN
      XL=LXS                                                            LAMBTN
      YL=LYS                                                            LAMBTN
      ZL=LZS                                                            LAMBTN
C....RANDOM LEAF ORIENTATION, DIRECTION COSINES OF NORMAL, AND           LAMBTN
C....LEAF OPTICAL PROPERTIES                                            LAMBTN
  100 IF(IDIR.EQ.-1) IXL=IL                                             LAMBTN
      IF(IDIR.EQ.1) IXL=NLAY-IL+1                                       LAMBTN
      CALL LANGLE(IXL,MTYPE,THETAL,PHIL)                                LAMBTN
C....SET SIDE OF LEAF WHICH LIGHT STRIKES. ISIDE=1 (TOP), -1 (BOTTOM).  LAMBTN
      ISIDE=-IDIR                                                       LAMBTN
      DOT=XL*XLF+YL*YLF+ZL*ZLF                                          LAMBTN
      IF(DOT.LT.0.) ISIDE=IDIR                                          LAMBTN
      COSLS=ABS(DOT)                                                    LAMBTN
      IF(IDIR.EQ.1) GO TO 5                                             LAMBTN
      DO 4 KL=1,NLAM                                                    LAMBTN
    4 H(KL)= DR(IL,JSOR,KL)/18.
      GO TO 9                                                           LAMBTN
    5 DO 7 KL=1,NLAM                                                    LAMBTN
    7 H(KL)= UR(IL,JSOR,KL)/18.
    9 CONTINUE                                                          LAMBTN
C...SET OPTICAL PROPERTIES FOR MTYPE,LAYER,REFLECT. AND TRANS.
C....UPDATE DIFFUSE SOURCES WITH SCATTERED RADIATION FLUX               LAMBTN
      DO 50 JJSOR=2,NSOUR                                               LAMBTN
      IF(ISIDE.EQ.-1) CALL BFLUX(THETAL,ZENITH(JJSOR),H,T,R,NLAM,PTRP)  LAMBTN
      IF(ISIDE.EQ.1) CALL BFLUX(THETAL,ZENITH(JJSOR),H,R,T,NLAM,PTRP)   LAMBTN
      DO 50 KL=1,NLAM                                                   LAMBTN
      IF(IDIR.EQ.1) GO TO 45                                            LAMBTN
      DR(IL+1,JJSOR,KL)=DR(IL+1,JJSOR,KL)+PTRP(2,KL)                    LAMBTN
      UR(NLAY+2-IL,JJSOR,KL)=UR(NLAY+2-IL,JJSOR,KL)+PTRP(1,KL)          LAMBTN
      GO TO 50                                                          LAMBTN
   45 DR(NLAY+2-IL,JJSOR,KL)=DR(NLAY+2-IL,JJSOR,KL)+PTRP(2,KL)          LAMBTN
      UR(IL+1,JJSOR,KL)=UR(IL+1,JJSOR,KL)+PTRP(1,KL)                    LAMBTN
   50 CONTINUE                                                          LAMBTN
      DO 53 KL=1,NLAM
      TABSO(IL,KL)=H(KL)    *(1.-(R(KL)+T(KL)))+TABSO(IL,KL)
   53 CONTINUE
```

```
      RETURN                                                          LAMBTN
      END                                                             LAMBTN
*DECK BFLUX
      SUBROUTINE BFLUX(TA,TRP,H,R,T,NLAM,PTRP)                         BFLUX
C.....GIVEN THE IRRADIANCE H OF A LEAF INCLINED AT TA THIS PROGRAM     BFLUX
C.....DETERMINES THE FLUX REFLECTED AND TRANSMITTED INTO A SOURCE      BFLUX
C.....BAND WHOSE ZENITH ANGLE IS TRP.                                  BFLUX
      DIMENSION PTRP(2,17),H(17),R(17),T(17)                           BFLUX
      DATA PI/3.141592654/,PIO2/1.570796327/                           BFLUX
      F1(X,Y)=COS(TA)*(SIN(X)**2-SIN(Y)**2)                            BFLUX
      F2(X)=ACOS(-1/(TAN(TA)*TAN(X)))                                  BFLUX
      F3(X,Y,Z)=2.*SIN(TA)*SIN(X)*(DEL+.25*(SIN(2.*Y)-SIN(2.*Z)))/PI   BFLUX
      DEL=.087266463                                                   BFLUX
      T1=TRP-DEL                                                       BFLUX
      T2=TRP+DEL                                                       BFLUX
      IF(TA.LE.PIO2-T2) GO TO 10                                       BFLUX
      IF(TA.GE.PIO2-T1) GO TO 20                                       BFLUX
      GO TO 30                                                         BFLUX
C....CASE 1                                                            BFLUX
   10 XF1=F1(T2,T1)                                                    BFLUX
      DO 15 KL=1,NLAM                                                  BFLUX
      PTRP(1,KL)=R(KL)*H(KL)*XF1                                       BFLUX
      PTRP(2,KL)=T(KL)*H(KL)*XF1                                       BFLUX
   15 CONTINUE                                                         BFLUX
      RETURN                                                           BFLUX
C....CASE 2                                                            BFLUX
   20 XF1=F1(T2,T1)                                                    BFLUX
      IF(TA.LE.1.5533) GO TO 21                                        BFLUX
      PRP=PIO2                                                         BFLUX
      GO TO 22                                                         BFLUX
   21 PRP=F2(TRP)                                                      BFLUX
   22 XF3=F3(PRP,T1,T2)                                                BFLUX
      DO 25 KL=1,NLAM                                                  BFLUX
      PTRP(1,KL)=H(KL)*(R(KL)+T(KL))*XF3+                              BFLUX
     1(R(KL)*H(KL)*PRP-T(KL)*H(KL)*PI+T(KL)*H(KL)*PRP)*XF1/PI          BFLUX
      PTRP(2,KL)=H(KL)*(T(KL)+R(KL))*XF3+                              BFLUX
     1(T(KL)*H(KL)*PRP-R(KL)*H(KL)*PI+R(KL)*H(KL)*PRP)*XF1/PI          BFLUX
   25 CONTINUE                                                         BFLUX
      RETURN                                                           BFLUX
C....CASE 3                                                            BFLUX
   30 TB=PIO2-TA                                                       BFLUX
      XF1=F1(TB,T1)                                                    BFLUX
      DO 35 KL=1,NLAM                                                  BFLUX
      PTRP(1,KL)=R(KL)*H(KL)*XF1                                       BFLUX
   35 PTRP(2,KL)=T(KL)*H(KL)*XF1                                       BFLUX
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      IF(TB+T2.LE.3.106) GO TO 36                                       BFLUX
      PRP=PI02                                                          BFLUX
      GO TO 37                                                          BFLUX
   36 PRP=F2((TB+T2)/2.)                                                BFLUX
   37 XF1=F1(T2,TB)                                                     BFLUX
      DEL=((TRP+TA)/2.)-.74176493                                       BFLUX
      XF3=F3(PRP,TB,T2)                                                 BFLUX
      DO 40 KL=1,NLAM                                                   BFLUX
      PTRP(1,KL)=PTRP(1,KL)+H(KL)*(R(KL)+T(KL))*XF3+                    BFLUX
     1(R(KL)*H(KL)*PRP-T(KL)*H(KL)*PI+T(KL)*H(KL)*PRP)*XF1/PI           BFLUX
      PTRP(2,KL)=PTRP(2,KL)+H(KL)*(T(KL)+R(KL))*XF3+                    BFLUX
     1(T(KL)*H(KL)*PRP-R(KL)*H(KL)*PI+R(KL)*H(KL)*PRP)*XF1/PI           BFLUX
   40 CONTINUE                                                          BFLUX
      RETURN                                                            BFLUX
      END                                                               BFLUX
*DECK LANGLE
      SUBROUTINE LANGLE(IL,MTYPE,THETAL,PHIL)                           LANGLE
C----THIS PROGRAM SELECTS A RANDOM LEAF INCLINATION (THETAL) AND AZIMUTH LANGLE
C    (PHIL) AND THEN COMPUTES ITS DIRECTION COSINES XLF, YLF, AND ZLF.  LANGLE
C    THE INTERMEDIATE PARAMETERS SINL, COSL, SINP, AND COSP ARE ALSO    LANGLE
C    OUTPUT.  RANDOM LEAF REFLECTANCE AND TRANSMITTANCE VECTORS ARE ALSO LANGLE
C    SELECTED.                                                          LANGLE
C                                                                       LANGLE
C    INPUT                                                              LANGLE
C      IL                                                               LANGLE
C      MTYPE                                                            LANGLE
C      NANGLE                                                           LANGLE
C    OUTPUT                                                             LANGLE
C      THETAL                                                           LANGLE
C      PHIL                                                             LANGLE
C      XLF, YLF, ZLF                                                    LANGLE
C      SINL, COSL, SINP, COSP                                           LANGLE
C      R,T
C                                                                       LANGLE
      COMMON/C1/DUM2(31),CERTD,DUM7(3),CE2PI                            LANGLE
      COMMON/C4/NANGLE(3,3),FLA(3,3,10),SLAI(3,3),FLAI(3,3),PHIT(3,3,10) LANGLE
      COMMON/C8/SINL,COSL,SINP,COSP                                     LANGLE
      COMMON DUM3(29),XLF,YLF,ZLF                                       LANGLE
      COMMON /KIM/ INL(3,3,2)
C----DETERMINE RANDOM LEAF ORIENTATION.                                 LANGLE
      FM=NANGLE(IL,MTYPE)                                               LANGLE
      XT=RANF(0.)                                                       LANGLE
      XI=1.+(FM-1.)*XT                                                  LANGLE
      IX=XI                                                             LANGLE
      IF(IX.EQ.NANGLE(IL,MTYPE)) IX=IX-1                                LANGLE
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      IXP1=IX+1                                                         LANGLE
      THETAL=FLA(IL,MTYPE,IX)+.5*(FLA(IL,MTYPE,IXP1)-FLA(IL,MTYPE,IX))  LANGLE
      PHIL=CE2PI*RANF(0.)                                               LANGLE
C----THETAL, PHIL ARE LEAF INCLINATION AND AZIMUTH, RESPECTIVELY.       LANGLE
1     CONTINUE                                                          LANGLE
      SINL=SIN(THETAL)                                                  LANGLE
      COSL=COS(THETAL)                                                  LANGLE
      SINP=SIN(PHIL)                                                    LANGLE
      COSP=COS(PHIL)                                                    LANGLE
C----COMPUTE LEAF NORMAL DIRECTION COSINES                              LANGLE
      XLF=-SINL*COSP                                                    LANGLE
      YLF=-SINL*SINP                                                    LANGLE
      ZLF=COSL                                                          LANGLE
C----SELECT RANDOM LEAF REFLECTANCE AND TRANSMITTANCE VECTORS.          LANGLE
      CALL OPTICAL(MTYPE,IL)
      RETURN                                                            LANGLE
      END                                                               LANGLE
*DECK COP
      SUBROUTINE COP(ALPHA,BETA,OP)                                     COP
C                                                                       COP
C....THIS PROGRAM CALCULATES THE MEAN PROJECTION OF A UNIT LEAF AREA IN COP
C....THE DIRECTION OF THE SOURCE.  THE LEAF IS INCLINED AT AN ANGLE     COP
C....ALPHA AND IS ASSUMED TO BE AZIMUTHALLY ISOTROPIC.  THE SOURCE      COP
C....DIRECTION IS AT AN AZIMUTH OF ZERO AND AN INCLINATION OF BETA.     COP
C                                                                       COP
      COMMON/C1/DUM1(33),CEPIO2                                         COP
      OP=COS(ALPHA)*SIN(BETA)                                           COP
      IF(ALPHA.LE.BETA) RETURN                                          COP
C....THETAO IS THE LEAF AZIMUTH ANGLE AT WHICH OP BECOMES NEGATIVE AND  COP
C....IS IN THE FIRST QUADRANT.  THE FUNCTION OP IS SYMMETRIC AND HENCE  COP
C....IS AVERAGED OVER LEAF AZIMUTH ANGLES OF 0 TO PI RADIANS.           COP
      THETAO=ACOS(TAN(BETA)/TAN(ALPHA))                                 COP
      TANTO=TAN(THETAO)                                                 COP
      OP=OP*(1.+(TANTO-THETAO)/CEPIO2)                                  COP
      RETURN                                                            COP
      END                                                               COP
*DECK COPM
      SUBROUTINE COPM(G,OP,OPM)                                         COPM
C....THIS PROGRAM CALCULATES THE MEAN PROJECTION OF A UNIT LEAF AREA IN COPM
C....THE DIRECTION OF THE SOURCE (OPM) FOR THE SIMULATED CANOPY.  THE   COPM
C....LEAVES OF THE CANOPY ARE ASSUMED TO BE AZIMUTHALLY ISOTROPIC.  THE COPM
C....OP FUNCTION USED IN THE CALCULATION HAS BEEN PREVIOUSLY DETERMINED COPM
C....FOR A GIVEN SOURCE DIRECTION FOR LEAF INCLINATION ANGLES OF        COPM
C....5, 15, ..., 85 DEGREES.  G IS THE LEAF INCLINATION ANGLE DENSITY   COPM
C....FUNCTION.                                                          COPM
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C                                                                       COPM
      DIMENSION OP(9),G(9)                                              COPM
      OPM=0.                                                            COPM
      DO 1 I=1,9                                                        COPM
    1 OPM=OPM+OP(I)*G(I)                                                COPM
      RETURN                                                            COPM
      END                                                               COPM
*DECK PDENS
      SUBROUTINE PDENS(IL,MTYPE,IANGLE,OPM)                             PDENS
C----THIS PROGRAM COMPUTES THE PROBABILITY THAT LIGHT AT INCIDENT ANGLE  PDENS
C     THETA(IANGLE) INTERACTS WITH MATERIAL TYPE MTYPE WITHIN CANOPY    PDENS
C     LAYER IL.                                                         PDENS
C                                                                       PDENS
C     INPUT                                                             PDENS
C       IL                                                              PDENS
C       MTYPE                                                           PDENS
C       IANGLE                                                          PDENS
C       OPM                                                             PDENS
C       SLAI                                                            PDENS
C       FLAI                                                            PDENS
C       THETA                                                           PDENS
C     OUTPUT                                                            PDENS
C       PHIT                                                            PDENS
C                                                                       PDENS
      COMMON/C2/DUM(289),THETA(10)
      COMMON/C4/NANGLE(3,3),FLA(3,3,10),SLAI(3,3),FLAI(3,3),PHIT(3,3,10) PDENS
      ARG=1.-(SLAI(IL,MTYPE)*OPM/SIN(THETA(IANGLE)))                    PDENS
      IF (ARG.LE.0.) GO TO 1                                            PDENS
      PO=ARG**(FLAI(IL,MTYPE)/SLAI(IL,MTYPE))                           PDENS
      GO TO 2                                                           PDENS
1     PO = 0.                                                           PDENS
      WRITE(6,100) IANGLE                                               PDENS
100   FORMAT (1H0, *   PO SET TO ZERO*,I5)                              PDENS
2     CONTINUE                                                          PDENS
      PHIT(IL,MTYPE,IANGLE)=1.-PO                                       PDENS
      RETURN                                                            PDENS
      END                                                               PDENS
*DECK PGAP
      SUBROUTINE PGAP(IL,IANGLE,IDIR,IHIT,MTYPE)                        PGAP
C----THIS PROGRAM DETERMINES IF AN INTERACTION IS BEING MADE IN LAYER IL PGAP
C     AND SETS THE MATERIAL TYPE OF LAYER IL.                           PGAP
C                                                                       PGAP
C     INPUT                                                             PGAP
C       IL                                                              PGAP
C       IANGLE                                                          PGAP
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C       IDIR                                                            PGAP
C       NLAY                                                            PGAP
C       MTP                                                             PGAP
C       PHIT                                                            PGAP
C     OUTPUT                                                            PGAP
C       IHIT                                                            PGAP
C       MTYPE                                                           PGAP
C                                                                       PGAP
      COMMON/C4/NANGLE(3,3),FLA(3,3,10),SLAI(3,3),FLAI(3,3),PHIT(3,3,10) PGAP
      COMMON/CMAT/MTP(3),NLAY                                           PGAP
      REAL PHITN
      IF(IDIR.LT.0) GO TO 10                                            PGAP
      ILAYER=NLAY+1-IL                                                  PGAP
      GO TO 20                                                          PGAP
   10 ILAYER=IL                                                         PGAP
C...MTP(ILAYER) GIVES THE LAST MTYPE WITHIN A LAYER WHICH CONTAINS THE COMBINED
C    MTYPE DISTRIBUTION.
   20 MTYPE=MTP(ILAYER)                                                 PGAP
      IHIT=0                                                            PGAP
      TEST=RANF(0.)                                                     PGAP
      IF(PHIT(ILAYER,MTYPE,IANGLE).LT.TEST) GO TO 30                    PGAP
      IHIT=1                                                            PGAP
      IF (MTYPE.EQ.1) GO TO 30
C...A HIT HAS BEEN RECORDED - NOW WHAT DID IT HIT.
C...NORMALIZE THE 2 MATERIAL DISTIBUTION TO 1.0
      PHITN  = PHIT(IL,1,IANGLE)/(PHIT(IL,1,IANGLE)+PHIT(IL,2,IANGLE))
      TEST =RANF(0.)
      IF (PHITN .LT.TEST) GO TO 40
      MTYPE = 1
      GO TO 30
   40 MTYPE = 2
   30 RETURN                                                            PGAP
      END                                                               PGAP
*DECK ETHRES
      SUBROUTINE ETHRES(NLAY,NSOUR,IDIR)                                ETHRES
C----THIS PROGRAM DETERMINES (FOR EACH LAYER AND FOR ALL LIGHT SOURCE   ETHRES
C     DIRECTIONS) IF THE SOURCE FLUX IS ABOVE THRESHOLD REQUIREMENTS IN ETHRES
C     THE DIRECTION INDICATED BY IDIR.  INDICATORS IGOD OR IGOU ARE SET ETHRES
C     ACCORDINGLY.                                                      ETHRES
C                                                                       ETHRES
C     INPUT                                                             ETHRES
C       NLAY                                                            ETHRES
C       NSOUR                                                           ETHRES
C       IDIR                                                            ETHRES
C       NLAM                                                            ETHRES
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C      DR                                                              ETHRES
C      UR                                                              ETHRES
C      THRES                                                           ETHRES
C    OUTPUT                                                            ETHRES
C      IGOD                                                            ETHRES
C      IGOU                                                            ETHRES
C                                                                      ETHRES
      COMMON/C1/DUMO(7),NLAM                                           ETHRES
      COMMON/C6/DR(4,10,17),UR(4,10,17),THRESD(10),IGOD(4,10),IGOU(4,10) ETHRES
     1,THRESU(10)                                                      ETHRES
C----DOWNWARD FLUX                                                     ETHRES
      IF(IDIR.GT.0) GO TO 10                                           ETHRES
      NLAYER=NLAY+1                                                    ETHRES
      DO 2 I=1,NLAYER                                                  ETHRES
      DO 2 J=1,NSOUR                                                   ETHRES
      IGOD(I,J)=0                                                      ETHRES
      DO 1 K=1,NLAM                                                    ETHRES
      IF(DR(I,J,K).LT.THRESD(J)) GO TO 1                               ETHRES
      IGOD(I,J)=1                                                      ETHRES
      GO TO 2                                                          ETHRES
    1 CONTINUE                                                         ETHRES
    2 CONTINUE                                                         ETHRES
      RETURN                                                           ETHRES
C----UPWARD FLUX                                                       ETHRES
10    CONTINUE                                                         ETHRES
      DO 4 I=1,NLAY                                                    ETHRES
      DO 4 J=2,NSOUR                                                   ETHRES
      IGOU(I,J)=0                                                      ETHRES
      DO 3 K=1,NLAM                                                    ETHRES
      IF(UR(I,J,K).LT.THRESU(J)) GO TO 3                               ETHRES
      IGOU(I,J)=1                                                      ETHRES
      GO TO 4                                                          ETHRES
    3 CONTINUE                                                         ETHRES
    4 CONTINUE                                                         ETHRES
      RETURN                                                           ETHRES
      END                                                              ETHRES
*DECK SETZ
      SUBROUTINE SETZ(IL,IANGLE,IDIR)                                  SETZ
C----THIS PROGRAM SETS THE FLUX (AND ITS APPROPRIATE INDICATORS) IN THE  SETZ
C    IDIR DIRECTION AT ANGLE THETA(IANGLE) IN LAYER IL TO ZERO.        SETZ
C                                                                      SETZ
C    INPUT                                                             SETZ
C      IL                                                              SETZ
C      IANGLE                                                          SETZ
C      IDIR                                                            SETZ
```

```
C       NLAM                                                            SETZ
C     OUTPUT                                                            SETZ
C       DR                                                              SETZ
C       UR                                                              SETZ
C       IGOD                                                            SETZ
C       IGOU                                                            SETZ
C                                                                       SETZ
      COMMON/C1/DUM1(7),NLAM                                            SETZ
      COMMON/C6/DR(4,10,17),UR(4,10,17),THRES(10),IGOD(4,10),IGOU(4,10) SETZ
      IF(IDIR.EQ.1) GO TO 10                                            SETZ
C----DOWNWARD FLUX                                                      SETZ
      DO 1 K=1,NLAM                                                     SETZ
    1 DR(IL,IANGLE,K)=0.                                                SETZ
      IGOD(IL,IANGLE)=0                                                 SETZ
      RETURN                                                            SETZ
C----UPWARD FLUX                                                        SETZ
10    CONTINUE                                                          SETZ
      DO 2 K=1,NLAM                                                     SETZ
    2 UR(IL,IANGLE,K)=0.                                                SETZ
      IGOU(IL,IANGLE)=0                                                 SETZ
      RETURN                                                            SETZ
      END                                                               SETZ
*DECK OPTICAL
      SUBROUTINE OPTICAL (MTYPE,IL)
C----THIS PROGRAM SELECTS RANDOM LEAF REFLECTANCE AND TRANSMITTANCE     OPTICAL
C    VECTORS FOR MATERIAL TYPE MTYPE.                                   OPTICAL
C                                                                       OPTICAL
C    INPUT                                                              OPTICAL
C       MTYPE                                                           OPTICAL
C       NVEC                                                            OPTICAL
C       C                                                               OPTICAL
C       XMU                                                             OPTICAL
C    OUTPUT                                                             OPTICAL
C       R,T
C                                                                       OPTICAL
      COMMON/L1/DATAID(7,9),XMU(17,9),C(17,17,9),NVEC(9)                OPTICAL
      COMMON/C2/CANRM(17),SKYIM(17),DIFIM(17),R(17),T(17),
     1RG(17),XLAM(17),SOURCE(10,17),THETA(10)
      COMMON /KIM/ INL(3,3,2)
C...SELECT APPROPRIATE OPTICAL VECTOR GIVEN MTYPE,IL,AND R OR T VECTOR.
      I= INL(IL,MTYPE,1)
      J=I+1                                                             OPTICAL
   11 CALL UTIL(XMU(1,I),R)
   13 CALL UTIL(XMU(1,J),T)
      RETURN                                                            OPTICAL
```

```
      END                                                                   OPTICAL
*DECK NRM
*DECK MATSQR
*DECK BLDATA
      BLOCK DATA                                                            BDAT
      COMMON/C1/DUM(30),CEDTR,CERTD,CEMTR,CEPIO2,CE1PI,CE2PI                BDAT
      DATA CEDTR,CERTD,CEMTR/.017453293,57.2957795,.00029088821/            BDAT
      DATA CEPIO2,CE1PI,CE2PI/1.57079632,3.14159265,6.28318530/             BDAT
      END                                                                   BDAT
*DECK TBLR
      SUBROUTINE TBLR(M, X, Y, XX, Z)                                       TBLR
C                                                                           TBLR
C....THIS PROGRAM FINDS THE INTEGRAL Z(X) OF THE FUNCTION Y(X) FROM X(1) TBLR
C....TO X(2M-1) USING SIMPSONS RULE   THE INTEGRAL Z(X) IS NORMALIZED TO TBLR
C....1.0 AT X(2M-1).  THE TABLE OF Z VERSUS X IS THEN INVERTED TO DETER- TBLR
C....MINE X AS A FUNCTION OF Z AT M REGULARLY SPACED POINTS ALONG Z.     TBLR
C                                                                           TBLR
C     INPUT VARIABLES                                                       TBLR
C       M   = DESIRED NUMBER OF REGULARLY SPACED POINTS ALONG Z             TBLR
C       X   = SPECIFIED AT 2M-1 POINTS                                      TBLR
C       Y   = SPECIFIED AT 2M-1 POINTS                                      TBLR
C     OUTPUT VARIABLES                                                      TBLR
C       XX = THE TABLE OF X VALUES FOR M REGULARLY SPACED POINTS            TBLR
C            (M-1 INTERVALS) ALONG Z.                                       TBLR
C       Z   = THE NORMALIZED INTEGRAL OF Y AT X(1), X(3), ..., X(2M-1).     TBLR
C                                                                           TBLR
      DIMENSION X(19),Y(19),Z(10),XI(10),XX(10)                             TBLR
C....SIMPSONS RULE INTEGRATION                                              TBLR
10    Z(1) = 0.0                                                            TBLR
      DX = X(2) - X(1)                                                      TBLR
20    DO 50 J = 2,M                                                         TBLR
      J0 = 2*J - 3                                                          TBLR
30    J1 = 2*J - 2                                                          TBLR
      J2 = 2*J - 1                                                          TBLR
40    Z(J) = Z(J - 1) + DX*(Y(J0) +4.*Y(J1) + Y(J2))/3.0                    TBLR
50    XI(J) = X(J2)                                                         TBLR
      XI(1)=X(1)                                                            TBLR
C....NORMALIZE INTEGRAL Z(X)                                                TBLR
60    DO 70 J = 1,M                                                         TBLR
70    Z(J) = Z(J)/Z(M)                                                      TBLR
C....FIND X AT M REGULARLY SPACED POINTS ALONG Z.                           TBLR
      XX(1) = X(1)                                                          TBLR
      EM = M - 1                                                            TBLR
      F = 1.0/EM                                                            TBLR
      JS=2                                                                  TBLR
```

```
80    DO 120 K = 2,M                                                      TBLR
      ZT = K - 1                                                          TBLR
      ZT = ZT*F                                                           TBLR
90    DO 110 J =JS,M                                                      TBLR
      IF(Z(J) - ZT) 110, 100, 100                                         TBLR
100   G = (ZT - Z(J - 1))    /(Z(J) - Z(J - 1))                           TBLR
      XX(K) = XI(J - 1) + G*(XI(J) - XI(J - 1))                           TBLR
      GO TO 115                                                           TBLR
110   CONTINUE                                                            TBLR
115   JS=J                                                                TBLR
120   CONTINUE                                                            TBLR
      RETURN                                                              TBLR
      END                                                                 TBLR
C
      SUBROUTINE SUN                                                      SUN
C----THIS PROGRAM CALCULATES THE POSITION OF THE SUN                      SUN
C                                                                         SUN
C    INPUT                                                                SUN
C      TIME                                                               SUN
C      GLAT                                                               SUN
C      DEC                                                                SUN
C    OUTPUT                                                               SUN
C      SINLAT, COSLAT                                                     SUN
C      SINDEC, COSDEC                                                     SUN
C      COSH                                                               SUN
C      SINZ, COSZ                                                         SUN
C      SINAZ, COSAZ                                                       SUN
C      LXS, LYS, LZS                                                      SUN
C                                                                         SUN
C        TIME OF SIMULATION (HOURS)                                       SUN
C        GLAT IS SITE GEOGRAPHICAL LATITUDE                               SUN
C        GLONG IS SITE LONGITUDE                                          SUN
C        DEC IS SOLAR DECLINATION                                         SUN
C        H IS SOLAR HOUR ANGLE                                            SUN
C        COSZ IS COSINE OF SOLAR ZENITH ANGLE                             SUN
C        COSAZ IS COSINE OF SOLAR AZIMUTH                                 SUN
C        LXS, LYS, LZS ARE SOLAR DIRECTION COSINES                        SUN
C                                                                         SUN
C                                                                         SUN
      COMMON/C1/DAY,YEAR,TIME,GLAT,GLONG,DEC,DUM(24),                     SUN
     1CEDTR,CERTD,CEMTR,DUM2(17),                                         SUN
     2SINLAT,COSLAT,SINDEC,COSDEC,COSH,SINZ,COSZ,SINAZ,COSAZ,LXS,LYS,LZS SUN
      REAL LXS,LYS.LZS                                                    SUN
      H=ABS(((12.-TIME)*15.)*CEDTR)                                       SUN
      SINLAT=SIN(GLAT)                                                    SUN
```

```
      COSLAT=COS(GLAT)                                              SUN
      SINDEC=SIN(DEC)                                               SUN
      COSDEC=COS(DEC)                                               SUN
      COSH=COS(H)                                                   SUN
      COSZ=SINLAT*SINDEC+COSLAT*COSDEC*COSH                         SUN
      SINZ=SQRT(1.-COSZ*COSZ)                                       SUN
      COSAZ=(SINDEC-SINLAT*COSZ)/(COSLAT*SINZ)                      SUN
      SINAZ=SQRT(1.-COSAZ*COSAZ)                                    SUN
      LXS=SINZ*COSAZ                                                SUN
      LYS=SINZ*SINAZ                                                SUN
      LZS=COSZ                                                      SUN
      RETURN                                                        SUN
      END                                                           SUN
C
      SUBROUTINE UTIL(A,B)                                          UTIL
C.....SET VECTOR B = VECTOR A                                       UTIL
      COMMON/C1/DUM(7),NLAM                                         UTIL
      DIMENSION A(17),B(17)                                         UTIL
      DO 1 I=1,NLAM                                                 UTIL
    1 B(I)=A(I)                                                     UTIL
      RETURN                                                        UTIL
      END                                                           UTIL
C
      SUBROUTINE FUN(A,B)                                           FUN
      RETURN                                                        FUN
      END                                                           FUN
```

APPENDIX B: GEOMETRICAL MATRICES FOR THEORETICAL CANOPIES

Planophile Canopy Geometry

FOLIAGE ANGLE DISTRIBUTION

INCLINATION ANGLE	PROBABILITY OF OCCURRENCE LAYER 1	LAYER 2	LAYER 3
0.0	.105	.105	.105
5.0	.104	.104	.104
10.0	.102	.102	.102
15.0	.098	.098	.098
20.0	.093	.093	.093
25.0	.086	.086	.086
30.0	.079	.079	.079
35.0	.071	.071	.071
40.0	.062	.062	.062
45.0	.053	.053	.053
50.0	.043	.043	.043
55.0	.035	.035	.035
60.0	.026	.026	.026
65.0	.019	.019	.019
70.0	.012	.012	.012
75.0	.007	.007	.007
80.0	.003	.003	.003
85.0	.001	.001	.001
90.0	0.000	0.000	0.000

CANOPY GEOMETRY INPUT DATA FOR PLANOPHILE,LAI=1

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
.25	.50	.25

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

	ZENITH ANGLE								
	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	.5606	.2652	.2094	.1913	.1846	.1820	.1812	.1810	.1810
LAYER 2	.3546	.3380	.2964	.2798	.2732	.2707	.2699	.2697	.2696
LAYER 3	.0476	.1052	.1035	.1012	.1001	.0996	.0995	.0994	.0994
GROUND	.0373	.2916	.3907	.4277	.4422	.4477	.4495	.4499	.4499

LONG WAVE TRANSFER MATRIX

	FROM				
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.8695	.2540	.3385	.1087	.4222
LAYER 2	.5973	.1663	.4657	.1663	.5973
LAYER 3	.4222	.1087	.3385	.2540	.8695

CANOPY GEOMETRY INPUT DATA FOR PLANOPHILE,LAI=4

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
1.00	2.00	1.00

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

	ZENITH ANGLE								
	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	.9627	.7084	.6093	.5723	.5578	.5523	.5505	.5501	.5501
LAYER 2	.0372	.2668	.3311	.3495	.3557	.3579	.3587	.3588	.3589
LAYER 3	0.0000	.0176	.0363	.0448	.0482	.0495	.0500	.0501	.0501
GROUND	0.0000	.0072	.0233	.0335	.0382	.0402	.0408	.0410	.0410

LONG WAVE TRANSFER MATRIX

	FROM				
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.5973	.7983	.4944	.0588	.0441
LAYER 2	.1578	.2196	1.2381	.2196	.1578
LAYER 3	.0441	.0588	.4944	.7983	.5973

CANOPY GEOMETRY INPUT DATA FOR PLANOPHILE,LAI=7

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
1.75	3.50	1.75

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

ZENITH ANGLE

	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	.9968	.8843	.8069	.7738	.7602	.7550	.7533	.7529	.7528
LAYER 2	.0032	.1141	.1859	.2146	.2260	.2303	.2317	.2321	.2321
LAYER 3	0.0000	.0014	.0058	.0090	.0105	.0111	.0113	.0114	.0114
GROUND	0.0000	.0002	.0014	.0026	.0033	.0036	.0037	.0037	.0037

LONG WAVE TRANSFER MATRIX

			FROM		
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.4222	1.1484	.4011	.0162	.0049
LAYER 2	.0441	.1516	1.6014	.1516	.0441
LAYER 3	.0049	.0162	.4011	1.1484	.4222

Erectophile Canopy Geometry

FOLIAGE ANGLE DISTRIBUTION

INCLINATION ANGLE	PROBABILITY OF OCCURRENCE LAYER 1	LAYER 2	LAYER 3
0.0	0.000	0.000	0.000
5.0	.001	.001	.001
10.0	.003	.003	.003
15.0	.007	.007	.007
20.0	.012	.012	.012
25.0	.019	.019	.019
30.0	.026	.026	.026
35.0	.035	.035	.035
40.0	.043	.043	.043
45.0	.053	.053	.053
50.0	.062	.062	.062
55.0	.071	.071	.071
60.0	.079	.079	.079
65.0	.086	.086	.086
70.0	.093	.093	.093
75.0	.098	.098	.098
80.0	.102	.102	.102
85.0	.104	.104	.104
90.0	.105	.105	.105

CANOPY GEOMETRY INPUT DATA FOR ERECTOPHILE,LAI=1

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
.25	.50	.25

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

	ZENITH ANGLE								
	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	.9056	.4333	.2770	.2036	.1620	.1365	.1204	.1109	.1064
LAYER 2	.0936	.3847	.3451	.2912	.2495	.2196	.1991	.1863	.1801
LAYER 3	.0008	.0789	.1047	.1028	.0953	.0879	.0820	.0780	.0759
GROUND	.0001	.1031	.2732	.4024	.4931	.5561	.5985	.6248	.6375

LONG WAVE TRANSFER MATRIX

	FROM				
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.7591	.4716	.3378	.0864	.3350
LAYER 2	.4764	.1540	.7292	.1540	.4764
LAYER 3	.3350	.0864	.3378	.4716	.7591

CANOPY GEOMETRY INPUT DATA FOR ERECTOPHILE,LAI=4

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
1.00	2.00	1.00

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

	ZENITH ANGLE								
	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	.9999	.8969	.7268	.5976	.5069	.4439	.4015	.3752	.3625
LAYER 2	.0001	.1020	.2528	.3372	.3732	.3841	.3841	.3809	.3784
LAYER 3	0.0000	.0010	.0148	.0389	.0608	.0763	.0861	.0915	.0939
GROUND	0.0000	.0001	.0056	.0262	.0591	.0956	.1283	.1524	.1652

LONG WAVE TRANSFER MATRIX

	FROM				
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.4764	1.0372	.3794	.0467	.0502
LAYER 2	.1377	.1627	1.3891	.1627	.1377
LAYER 3	.0502	.0467	.3794	1.0372	.4764

CANOPY GEOMETRY INPUT DATA FOR ERECTOPHILE,LAI=7

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
1.75	3.50	1.75

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

	ZENITH ANGLE								
	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	1.0000	.9812	.8967	.7967	.7098	.6419	.5928	.5609	.5451
LAYER 2	0.0000	.0188	.1022	.1949	.2657	.3122	.3397	.3544	.3607
LAYER 3	0.0000	0.0000	.0010	.0067	.0173	.0295	.0400	.0475	.0513
GROUND	0.0000	0.0000	.0001	.0017	.0071	.0164	.0275	.0372	.0428

LONG WAVE TRANSFER MATRIX

			FROM		
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.3350	1.3200	.3057	.0188	.0105
LAYER 2	.0502	.1151	1.6592	.1151	.0502
LAYER 3	.0105	.0188	.3057	1.3200	.3350

Plagiophile Canopy Geometry

FOLIAGE ANGLE DISTRIBUTION

INCLINATION ANGLE	PROBABILITY OF OCCURRENCE LAYER 1	LAYER 2	LAYER 3
0.0	0.000	0.000	0.000
5.0	.003	.003	.003
10.0	.013	.013	.013
15.0	.028	.028	.028
20.0	.046	.046	.046
25.0	.065	.065	.065
30.0	.083	.083	.083
35.0	.098	.098	.098
40.0	.108	.108	.108
45.0	.111	.111	.111
50.0	.108	.108	.108
55.0	.098	.098	.098
60.0	.083	.083	.083
65.0	.065	.065	.065
70.0	.046	.046	.046
75.0	.028	.028	.028
80.0	.013	.013	.013
85.0	.003	.003	.003
90.0	0.000	0.000	0.000

CANOPY GEOMETRY INPUT DATA FOR PLAGIOPHILE,LAI=1

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
.25	.50	.25

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

ZENITH ANGLE

	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	.8005	.3622	.2461	.2003	.1801	.1716	.1684	.1676	.1676
LAYER 2	.1916	.3784	.3254	.2883	.2688	.2599	.2565	.2557	.2556
LAYER 3	.0064	.0940	.1055	.1024	.0993	.0975	.0969	.0967	.0967
GROUND	.0016	.1654	.3230	.4090	.4518	.4710	.4782	.4800	.4802

LONG WAVE TRANSFER MATRIX

	FROM				
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.8124	.3680	.3525	.0976	.3622
LAYER 2	.5212	.1665	.6173	.1665	.5212
LAYER 3	.3622	.0976	.3525	.3680	.8124

CANOPY GEOMETRY INPUT DATA FOR PLAGIOPHILE,LAI=4

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
1.00	2.00	1.00

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

	ZENITH ANGLE								
	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	.9984	.8346	.6770	.5910	.5482	.5290	.5218	.5200	.5198
LAYER 2	.0016	.1609	.2893	.3406	.3596	.3665	.3688	.3694	.3695
LAYER 3	0.0000	.0038	.0228	.0404	.0506	.0553	.0571	.0575	.0575
GROUND	0.0000	.0007	.0109	.0280	.0417	.0492	.0523	.0531	.0532

LONG WAVE TRANSFER MATRIX

	FROM				
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.5212	.9503	.4337	.0491	.0384
LAYER 2	.1335	.1892	1.3475	.1892	.1335
LAYER 3	.0384	.0491	.4337	.9503	.5212

CANOPY GEOMETRY INPUT DATA FOR PLAGIOPHILE,LAI=7

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
1.75	3.50	1.75

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

ZENITH ANGLE

	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	1.0000	.9571	.8616	.7908	.7510	.7322	.7250	.7232	.7230
LAYER 2	0.0000	.0428	.1357	.2000	.2335	.2486	.2542	.2556	.2557
LAYER 3	0.0000	.0001	.0023	.0072	.0116	.0141	.0151	.0153	.0154
GROUND	0.0000	0.0000	.0004	.0019	.0038	.0051	.0057	.0059	.0059

LONG WAVE TRANSFER MATRIX

			FROM		
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.3622	1.2683	.3433	.0142	.0047
LAYER 2	.0384	.1271	1.6617	.1271	.0384
LAYER 3	.0047	.0142	.3433	1.2683	.3622

FOLIAGE ANGLE DISTRIBUTION

INCLINATION ANGLE	PROBABILITY OF OCCURRENCE LAYER 1	LAYER 2	LAYER 3
0.0	.100	.100	.100
5.0	.097	.097	.097
10.0	.088	.088	.088
15.0	.075	.075	.075
20.0	.059	.059	.059
25.0	.041	.041	.041
30.0	.025	.025	.025
35.0	.012	.012	.012
40.0	.003	.003	.003
45.0	0.000	0.000	0.000
50.0	.003	.003	.003
55.0	.012	.012	.012
60.0	.025	.025	.025
65.0	.041	.041	.041
70.0	.059	.059	.059
75.0	.075	.075	.075
80.0	.088	.088	.088
85.0	.097	.097	.097
90.0	.100	.100	.100

CANOPY GEOMETRY INPUT DATA FOR EXTREMOPHILE,LAI=1

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
.25	.50	.25

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

	ZENITH ANGLE								
	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	.7427	.3437	.2414	.1949	.1672	.1484	.1354	.1270	.1228
LAYER 2	.2403	.3736	.3221	.2832	.2552	.2340	.2183	.2077	.2023
LAYER 3	.0126	.0972	.1054	.1017	.0966	.0917	.0875	.0845	.0829
GROUND	.0044	.1855	.3311	.4202	.4811	.5259	.5588	.5808	.5920

LONG WAVE TRANSFER MATRIX

	FROM				
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.8350	.3202	.3383	.0971	.3995
LAYER 2	.5572	.1618	.5521	.1618	.5572
LAYER 3	.3995	.0971	.3383	.3202	.8350

CANOPY GEOMETRY INPUT DATA FOR EXTREMOPHILE,LAI=4

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
1.00	2.00	1.00

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

	ZENITH ANGLE								
	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	.9956	.8145	.6689	.5798	.5189	.4741	.4412	.4192	.4080
LAYER 2	.0044	.1792	.2948	.3460	.3697	.3804	.3843	.3849	.3845
LAYER 3	0.0000	.0052	.0243	.0430	.0578	.0690	.0770	.0821	.0846
GROUND	0.0000	.0012	.0120	.0312	.0536	.0765	.0975	.1138	.1228

LONG WAVE TRANSFER MATRIX

	FROM				
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.5572	.8756	.4436	.0576	.0561
LAYER 2	.1643	.1956	1.2704	.1956	.1643
LAYER 3	.0561	.0576	.4436	.8756	.5572

CANOPY GEOMETRY INPUT DATA FOR EXTREMOPHILE,LAI=7

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
1.75	3.50	1.75

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

	ZENITH ANGLE								
	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	.9999	.9482	.8566	.7821	.7236	.6768	.6404	.6152	.6020
LAYER 2	.0001	.0517	.1404	.2074	.2550	.2891	.3127	.3274	.3344
LAYER 3	0.0000	.0001	.0020	.0061	.0111	.0162	.0207	.0241	.0259
GROUND	0.0000	0.0000	.0010	.0044	.0103	.0179	.0262	.0334	.0376

LONG WAVE TRANSFER MATRIX

	FROM				
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.3983	1.1936	.3674	.0149	.0160
LAYER 2	.0558	.1427	1.5931	.1036	.0949
LAYER 3	.0125	.0273	.5174	.8756	.5572

Spherical Canopy Geometry

FOLIAGE ANGLE DISTRIBUTION

INCLINATION ANGLE	PROBABILITY OF OCCURRENCE LAYER 1	LAYER 2	LAYER 3
0.0	.056	.056	.056
5.0	.056	.056	.056
10.0	.056	.056	.056
15.0	.056	.056	.056
20.0	.056	.056	.056
25.0	.056	.056	.056
30.0	.056	.056	.056
35.0	.056	.056	.056
40.0	.056	.056	.056
45.0	.056	.056	.056
50.0	.056	.056	.056
55.0	.056	.056	.056
60.0	.056	.056	.056
65.0	.056	.056	.056
70.0	.056	.056	.056
75.0	.056	.056	.056
80.0	.056	.056	.056
85.0	.056	.056	.056
90.0	.056	.056	.056

CANOPY GEOMETRY INPUT DATA FOR SPHERICAL,LAI=1

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
.25	.50	.25

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

	ZENITH ANGLE								
	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	.7712	.3525	.2437	.1975	.1733	.1594	.1511	.1464	.1442
LAYER 2	.2169	.3760	.3237	.2856	.2617	.2467	.2372	.2316	.2290
LAYER 3	.0092	.0957	.1054	.1021	.0979	.0947	.0924	.0911	.0904
GROUND	.0027	.1758	.3273	.4148	.4670	.4992	.5192	.5309	.5364

LONG WAVE TRANSFER MATRIX

	FROM				
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.8244	.3427	.3455	.0974	.3814
LAYER 2	.5398	.1643	.5832	.1643	.5398
LAYER 3	.3814	.0974	.3455	.3427	.8244

CANOPY GEOMETRY INPUT DATA FOR SPHERICAL,LAI=4

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
1.00	2.00	1.00

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

	ZENITH ANGLE								
	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	.9973	.8242	.6727	.5852	.5330	.5008	.4808	.4691	.4636
LAYER 2	.0027	.1703	.2922	.3435	.3652	.3748	.3792	.3813	.3821
LAYER 3	0.0000	.0045	.0236	.0418	.0543	.0623	.0673	.0702	.0715
GROUND	0.0000	.0010	.0115	.0296	.0476	.0621	.0727	.0794	.0828

LONG WAVE TRANSFER MATRIX

	FROM				
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.5398	.9118	.4395	.0536	.0468
LAYER 2	.1489	.1928	1.3079	.1928	.1489
LAYER 3	.0468	.0536	.4395	.9118	.5398

CANOPY GEOMETRY INPUT DATA FOR SPHERICAL,LAI=7

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
1.75	3.50	1.75

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

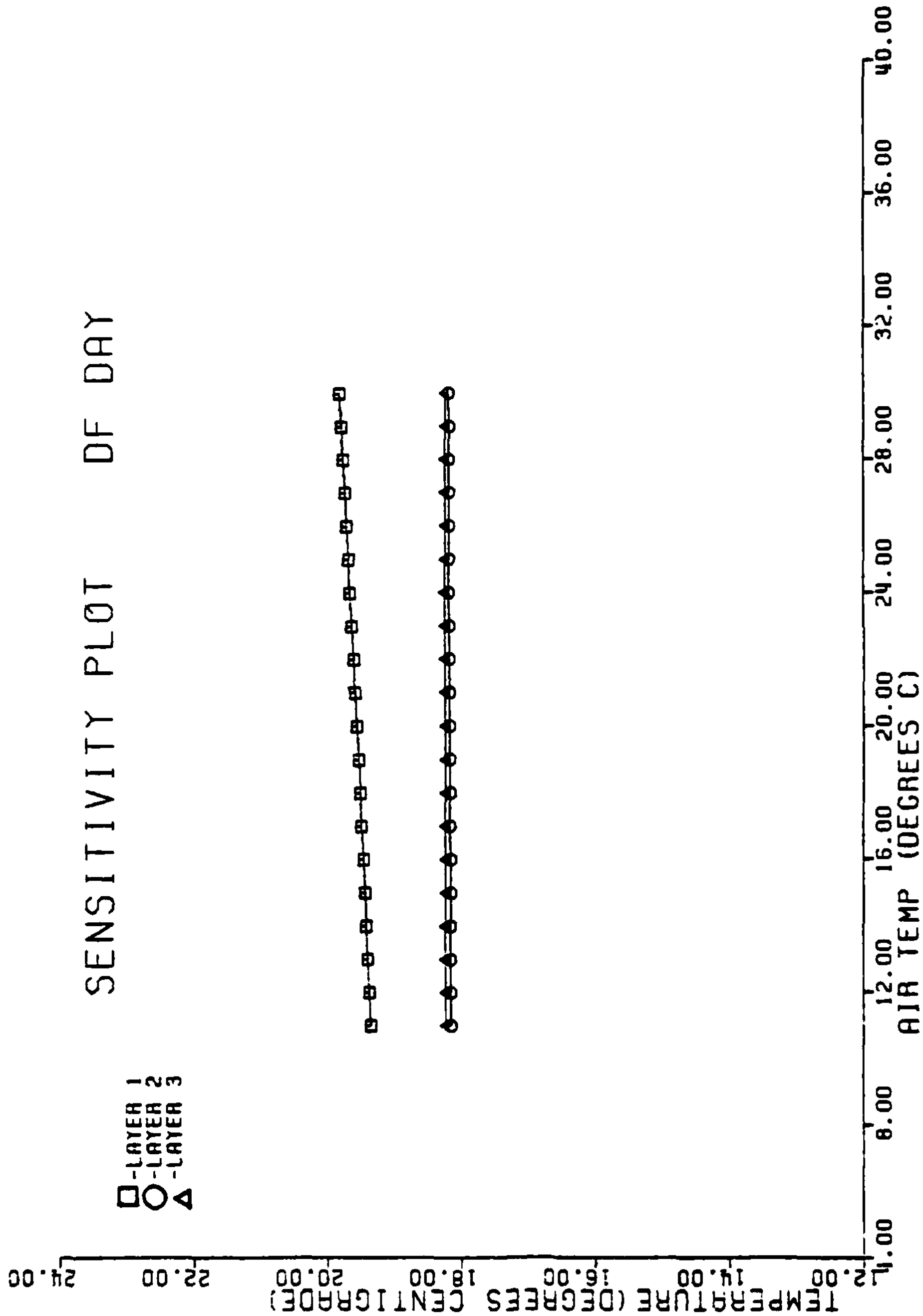
	ZENITH ANGLE								
	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	1.0000	.9523	.8584	.7856	.7362	.7035	.6824	.6698	.6638
LAYER 2	0.0000	.0476	.1388	.2046	.2455	.2704	.2855	.2942	.2982
LAYER 3	0.0000	.0001	.0024	.0077	.0135	.0183	.0219	.0241	.0252
GROUND	0.0000	0.0000	.0004	.0021	.0048	.0077	.0102	.0119	.0128

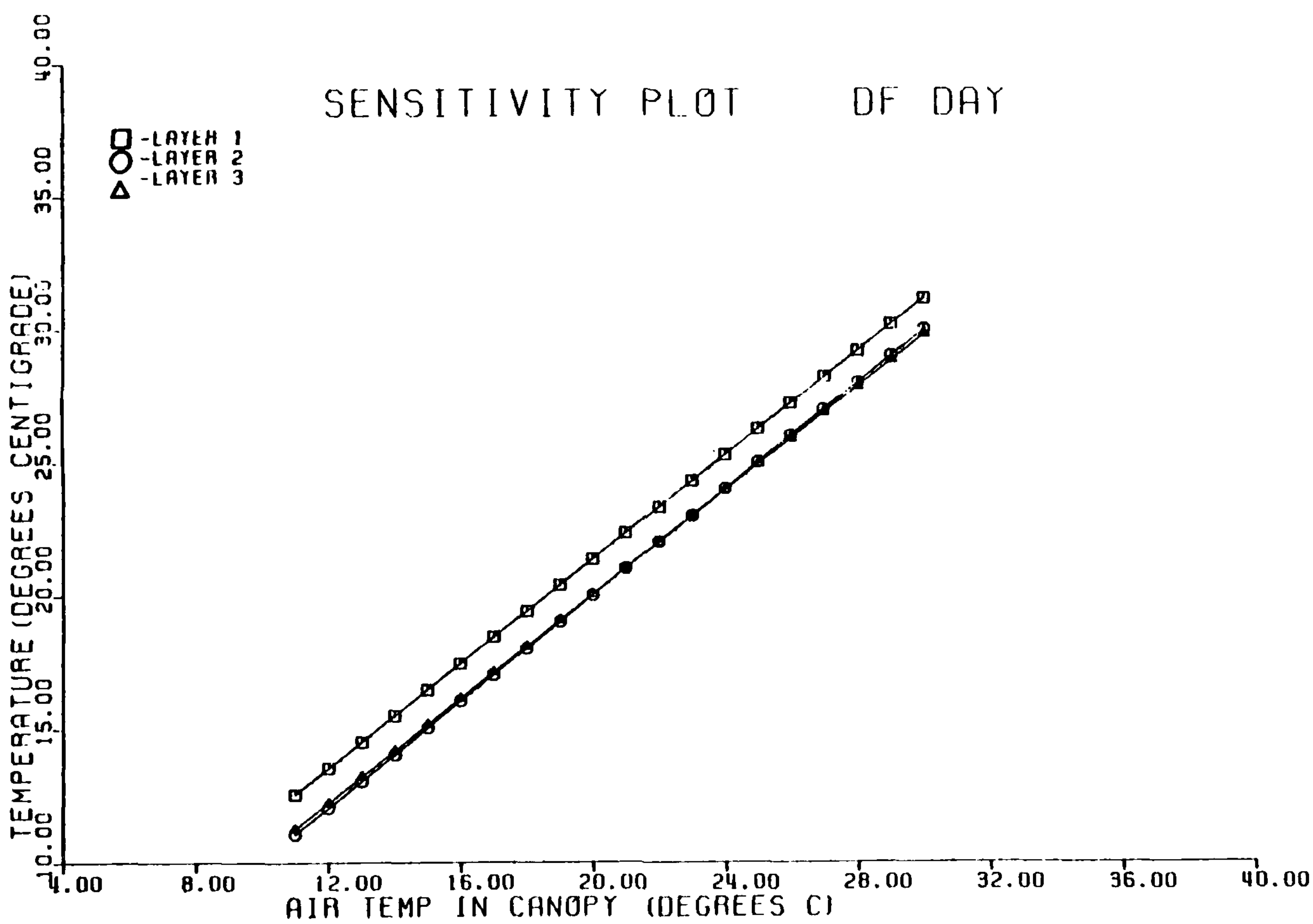
LONG WAVE TRANSFER MATRIX

	FROM				
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.3814	1.2286	.3570	.0175	.0069
LAYER 2	.0468	.1354	1.6271	.1354	.0468
LAYER 3	.0069	.0175	.3570	1.2286	.3814

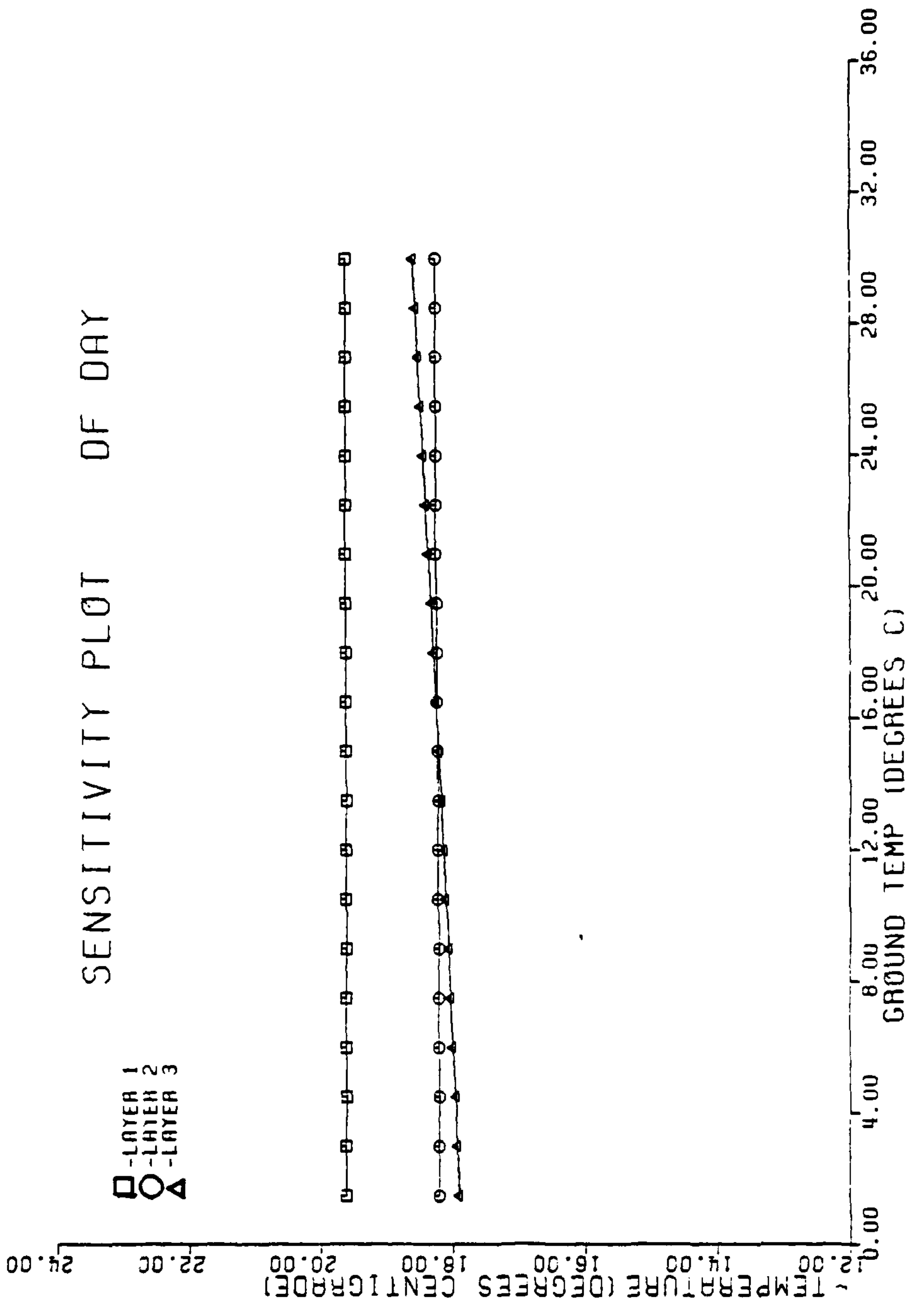
APPENDIX C: SENSITIVITY ANALYSIS RESULTS

Douglas-Fir Daytime Sensitivity Plots

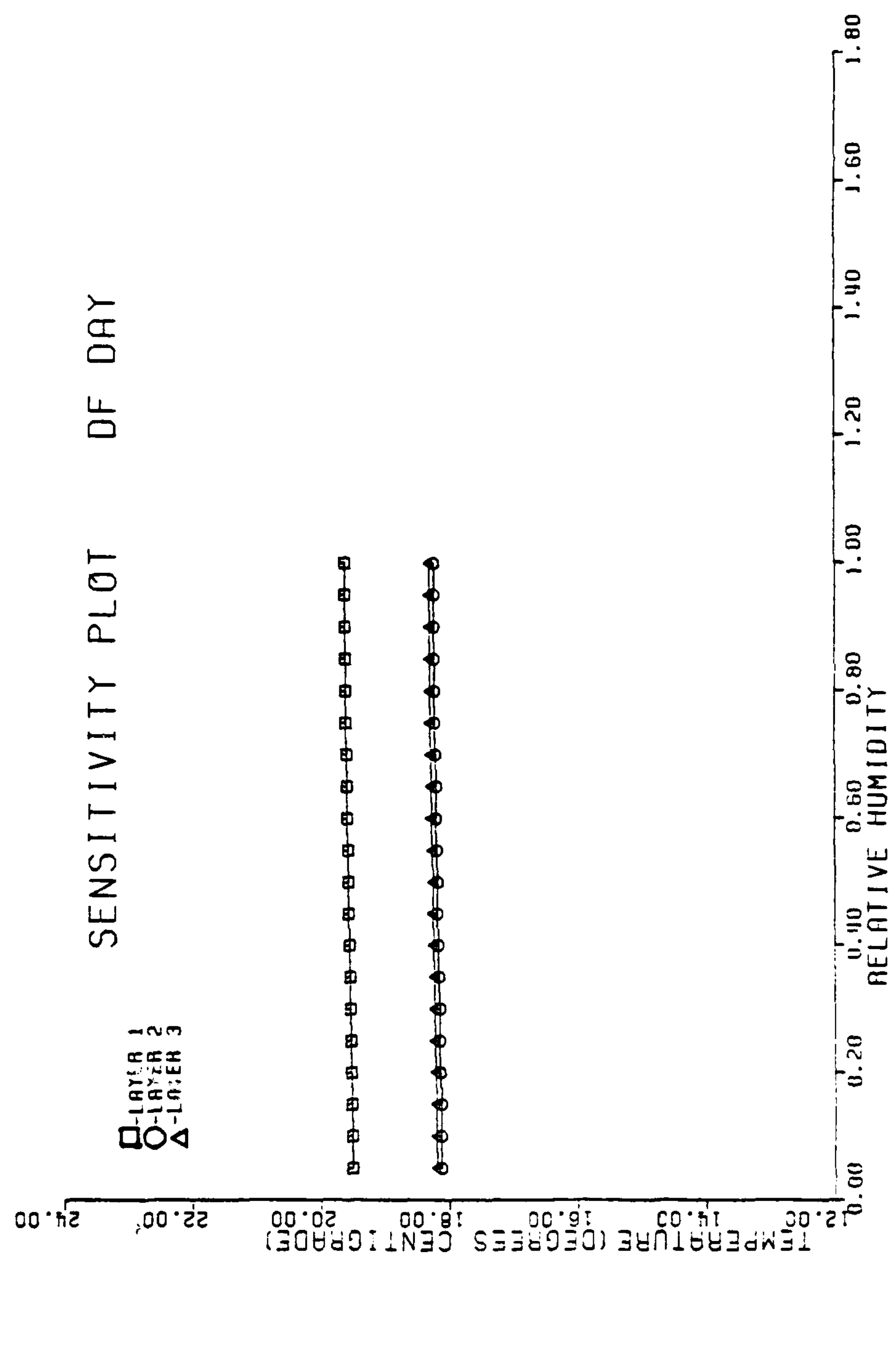

SENSITIVITY PLØT OF DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00
AIR TEMP (DEGREES C)
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
40.00



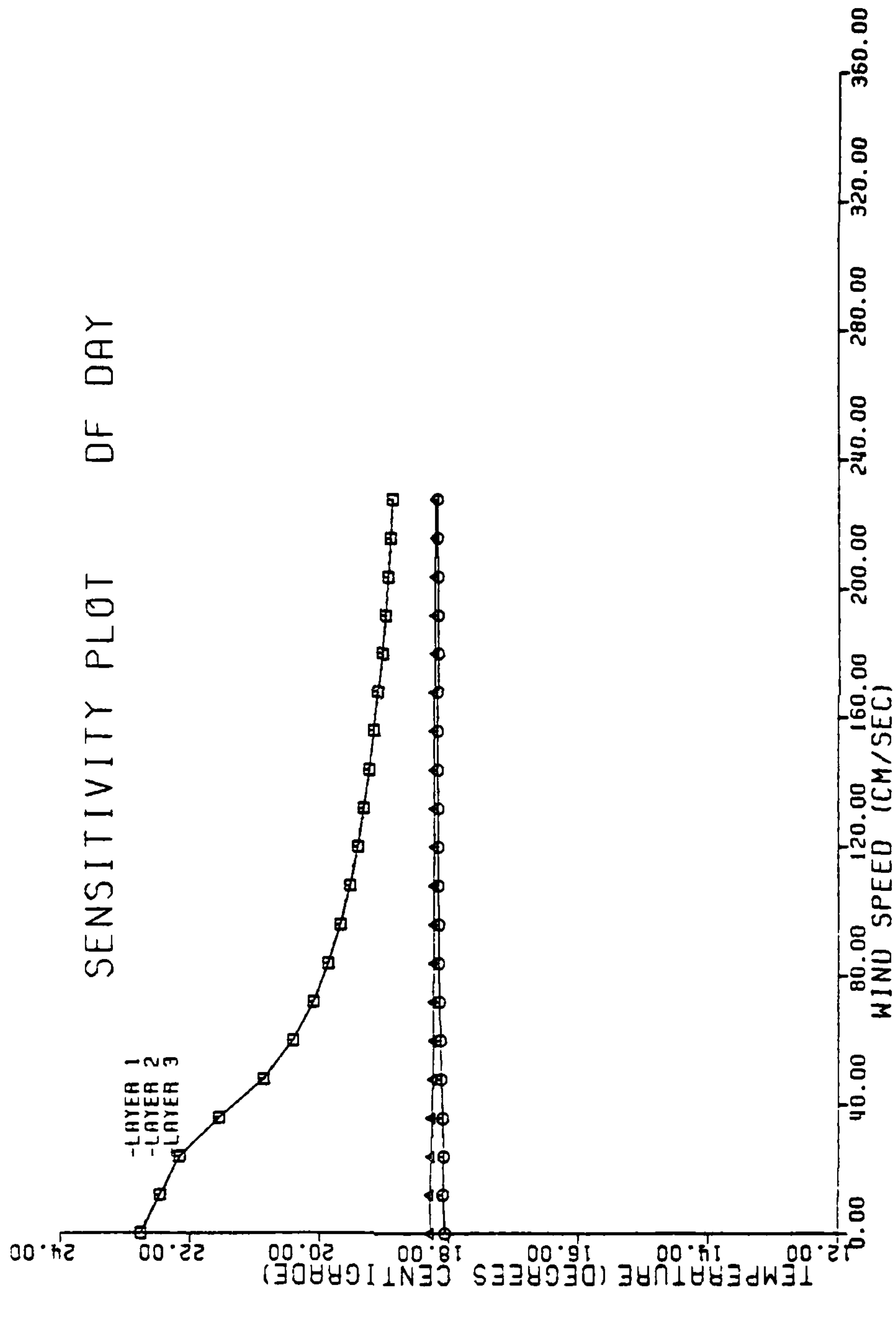
SENSITIVITY PLOT OF DAY
□ -LAYER 1
○ -LAYER 2
△ -LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
10.00
15.00
20.00
25.00
30.00
35.00
40.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
40.00
AIR TEMP IN CANOPY (DEGREES C)

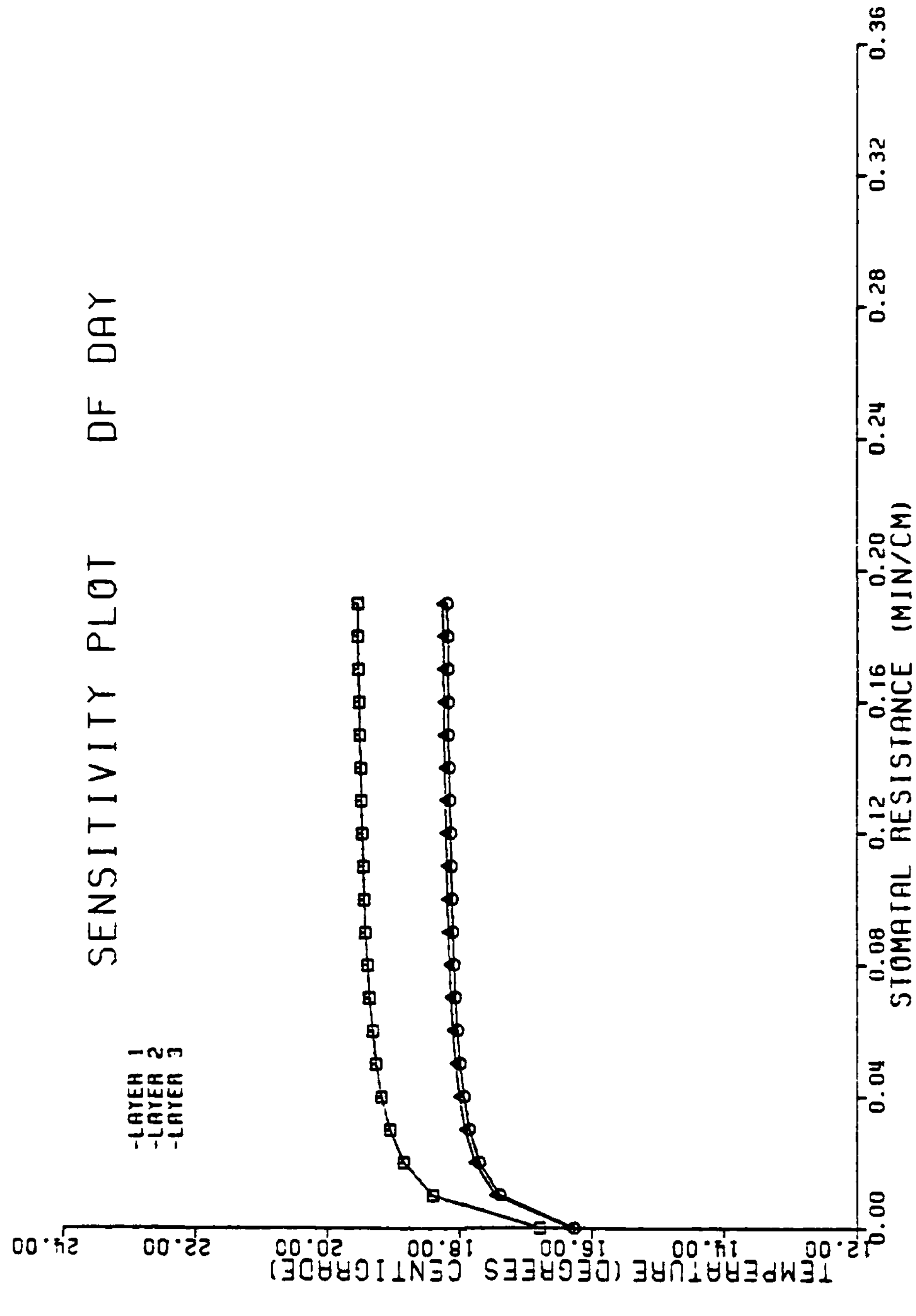


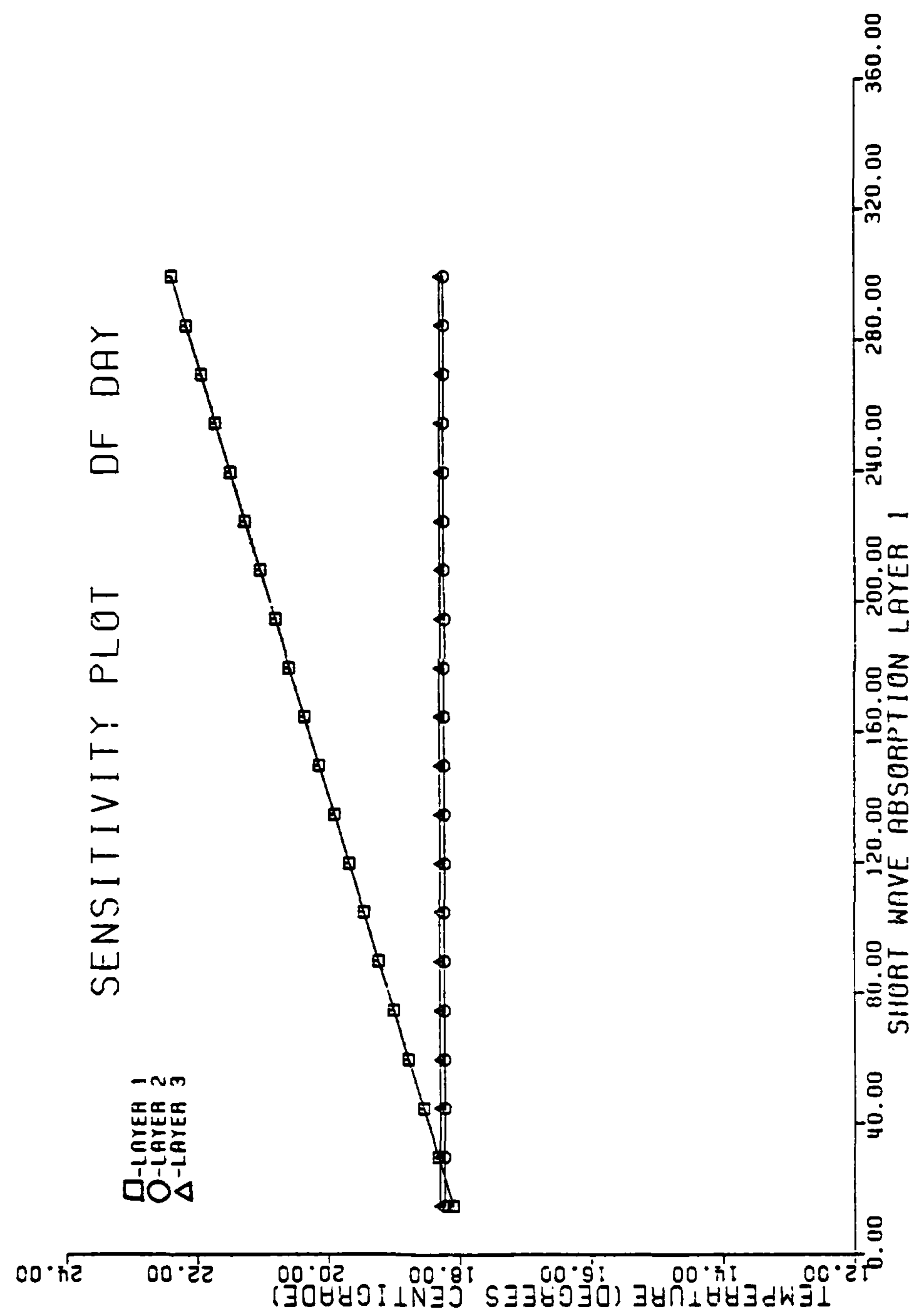
SENSITIVITY PLOT OF DAY
-LAYER 1
-LAYER 2
-LAYER 3
GROUND TEMP (DEGREES C)
TEMPERATURE (DEGREES CENTIGRADE)
0.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00



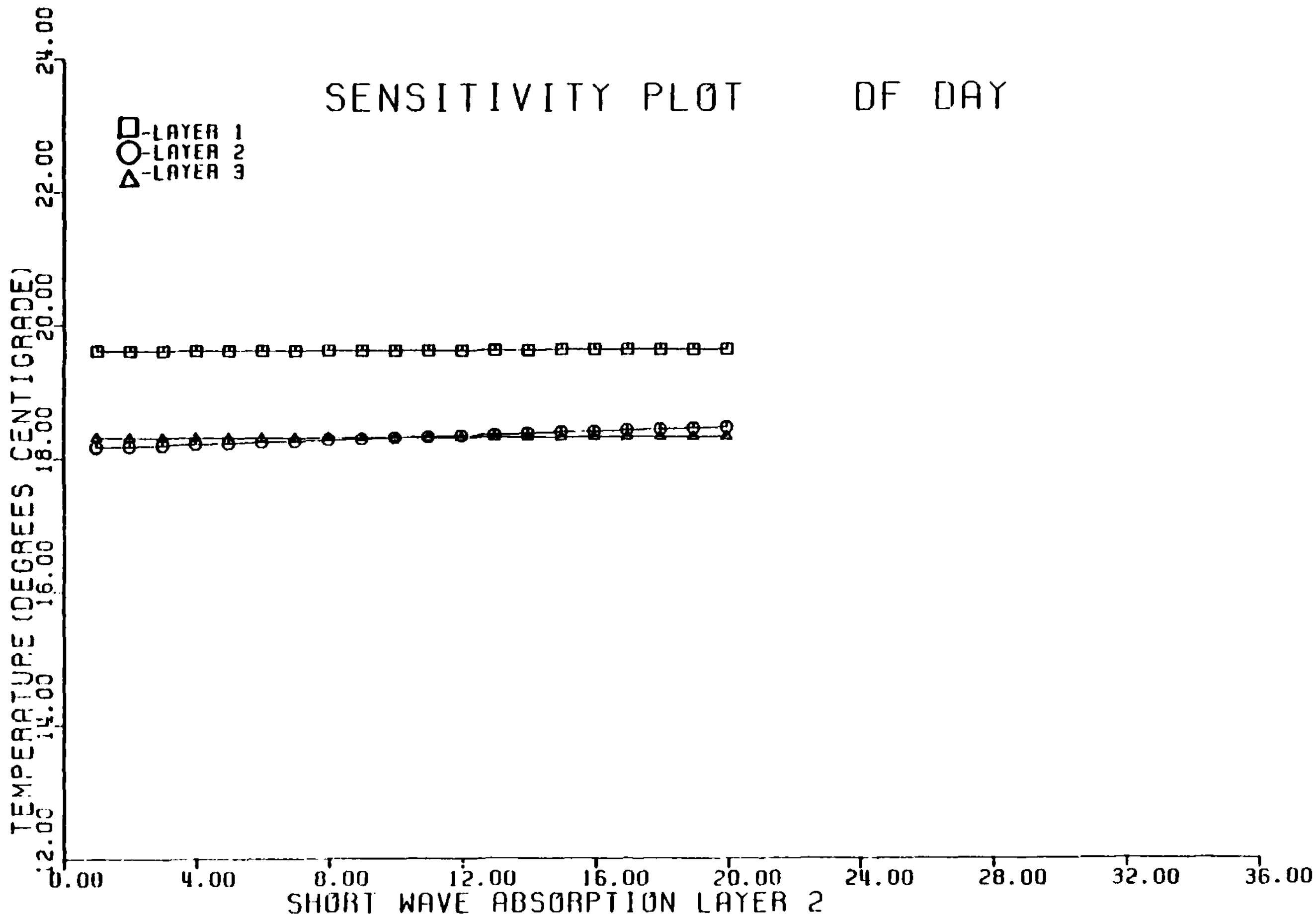
SENSITIVITY PLØT OF DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
RELATIVE HUMIDITY
12.00
14.00
16.00
18.00
20.00
22.00
24.00
TEMPERATURE (DEGREES CENTIGRADE)


SENSITIVITY PLOT OF DAY
-LAYER 1
-LAYER 2
-LAYER 3
WIND SPEED (CM/SEC)
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280.00
320.00
360.00
TEMPERATURE(DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00

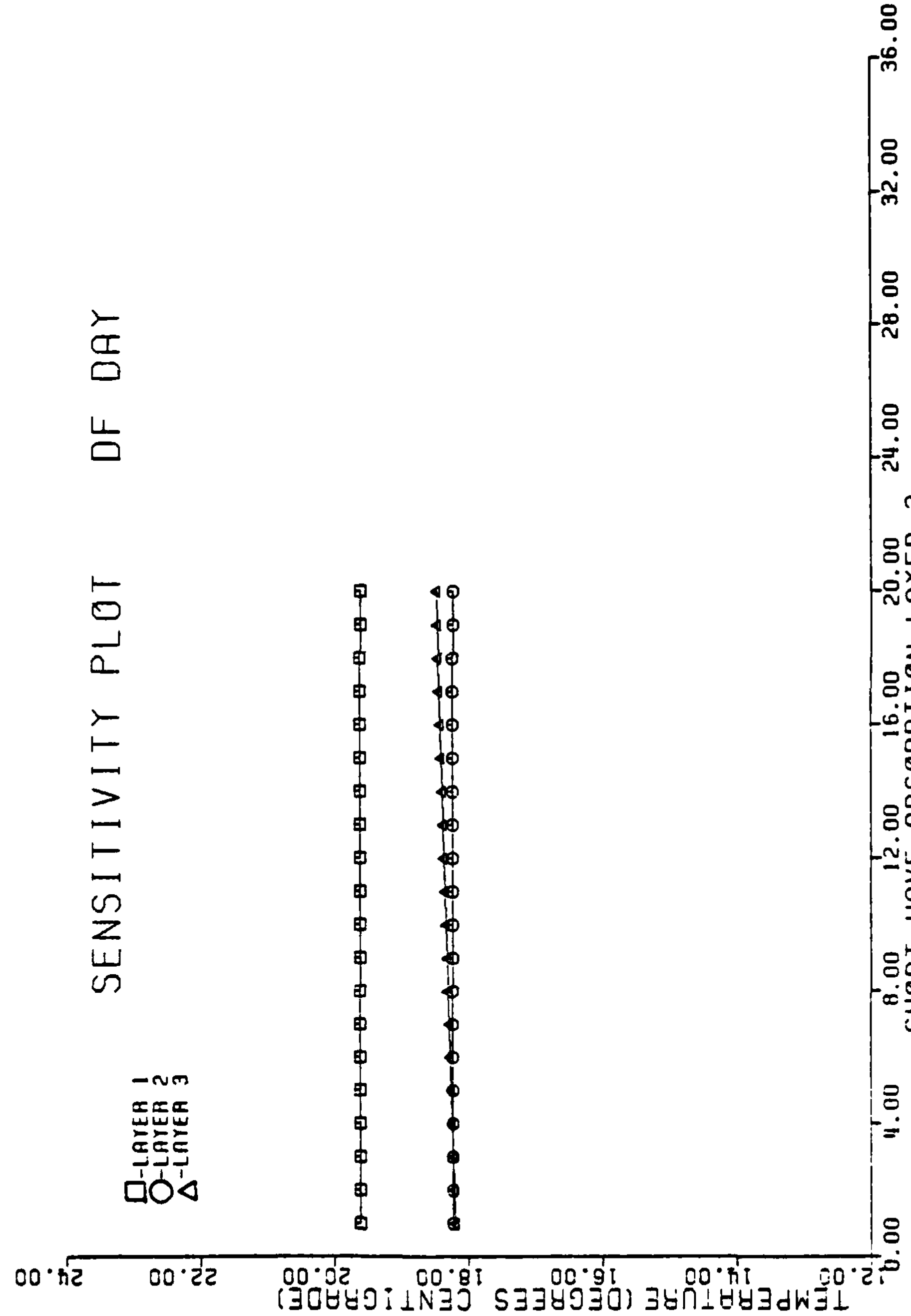

SENSITIVITY PLOT OF DAY
-LAYER 1
-LAYER 2
-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00
STOMATAL RESISTANCE (MIN/CM)
0.00
0.04
0.08
0.12
0.16
0.20
0.24
0.28
0.32
0.36

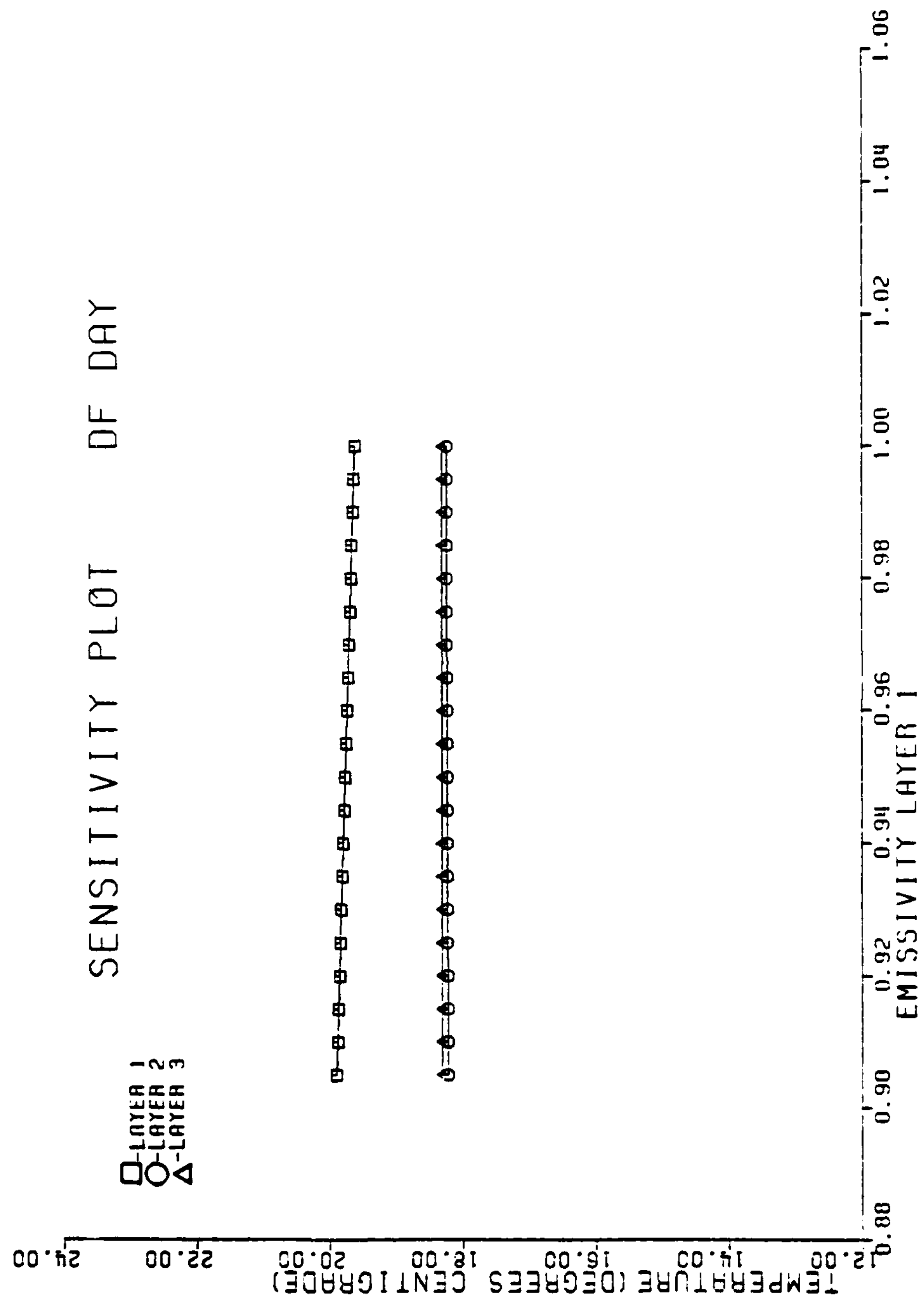


SENSITIVITY PLOT DF DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
SHORT WAVE ABSORPTION LAYER 1
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280.00
320.00
360.00
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00

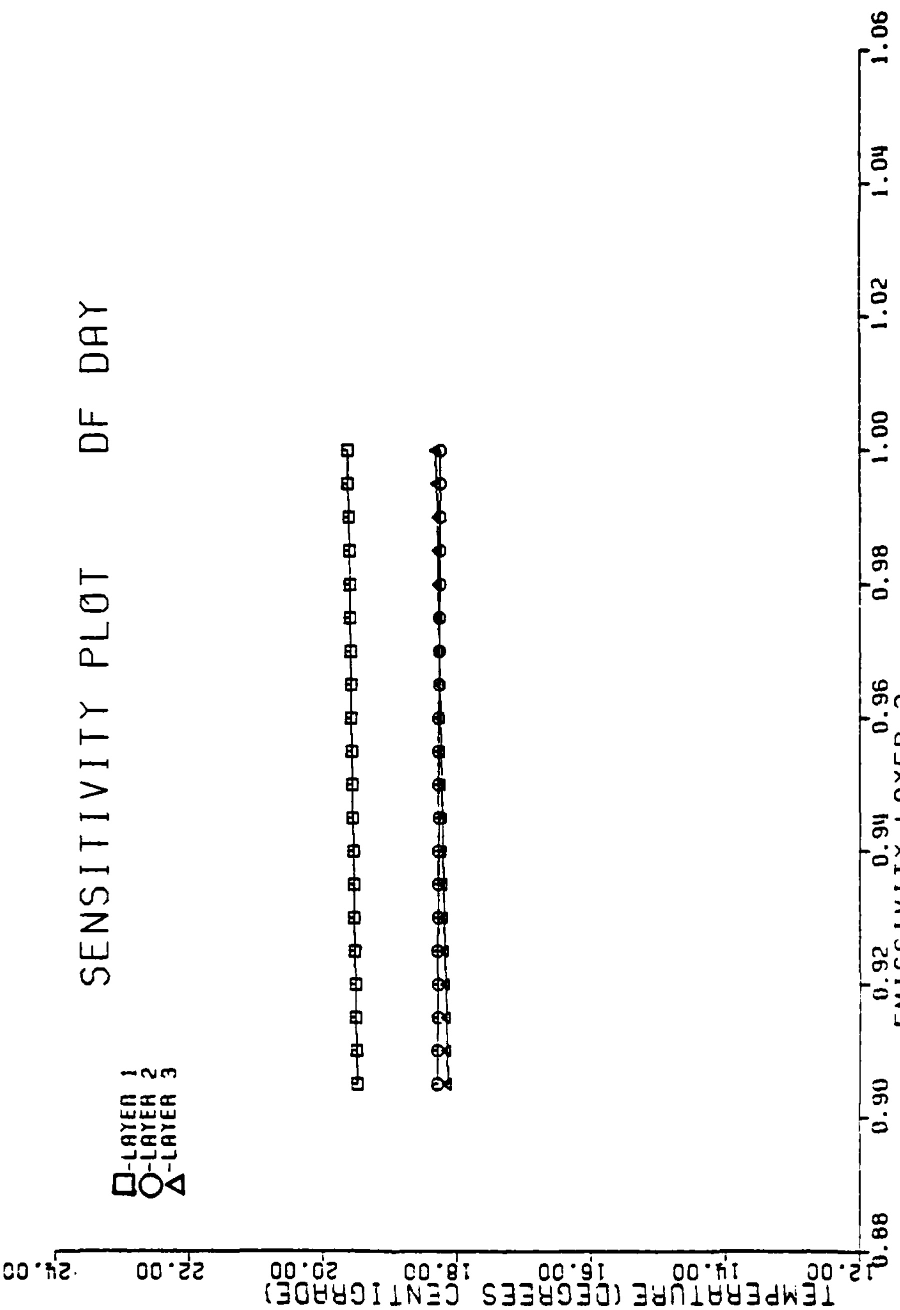


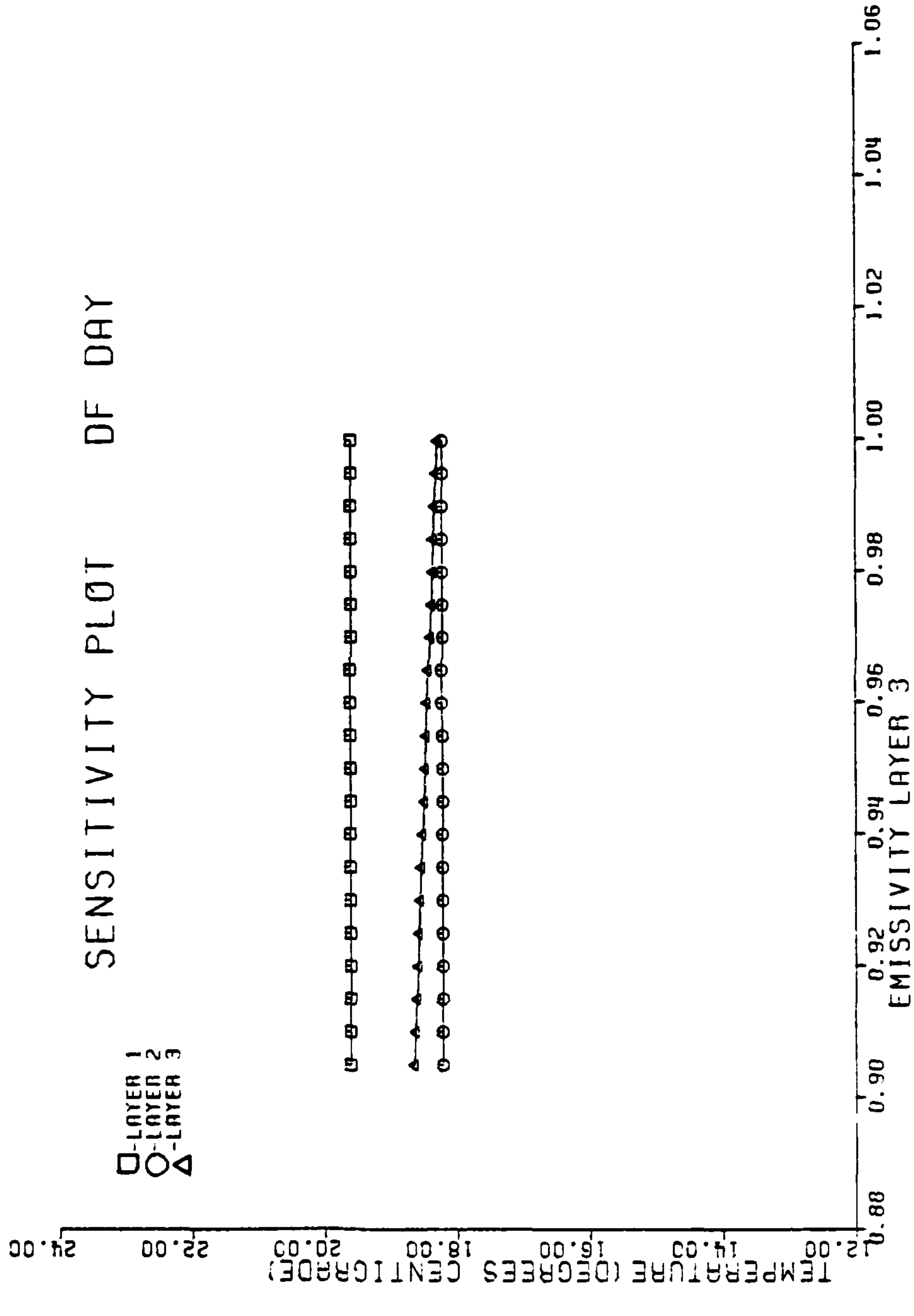
SENSITIVITY PLOT OF DAY
-LAYER 1
-LAYER 2
-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
24.00
22.00
20.00
18.00
16.00
14.00
12.00
0.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
SHORT WAVE ABSORPTION LAYER 2

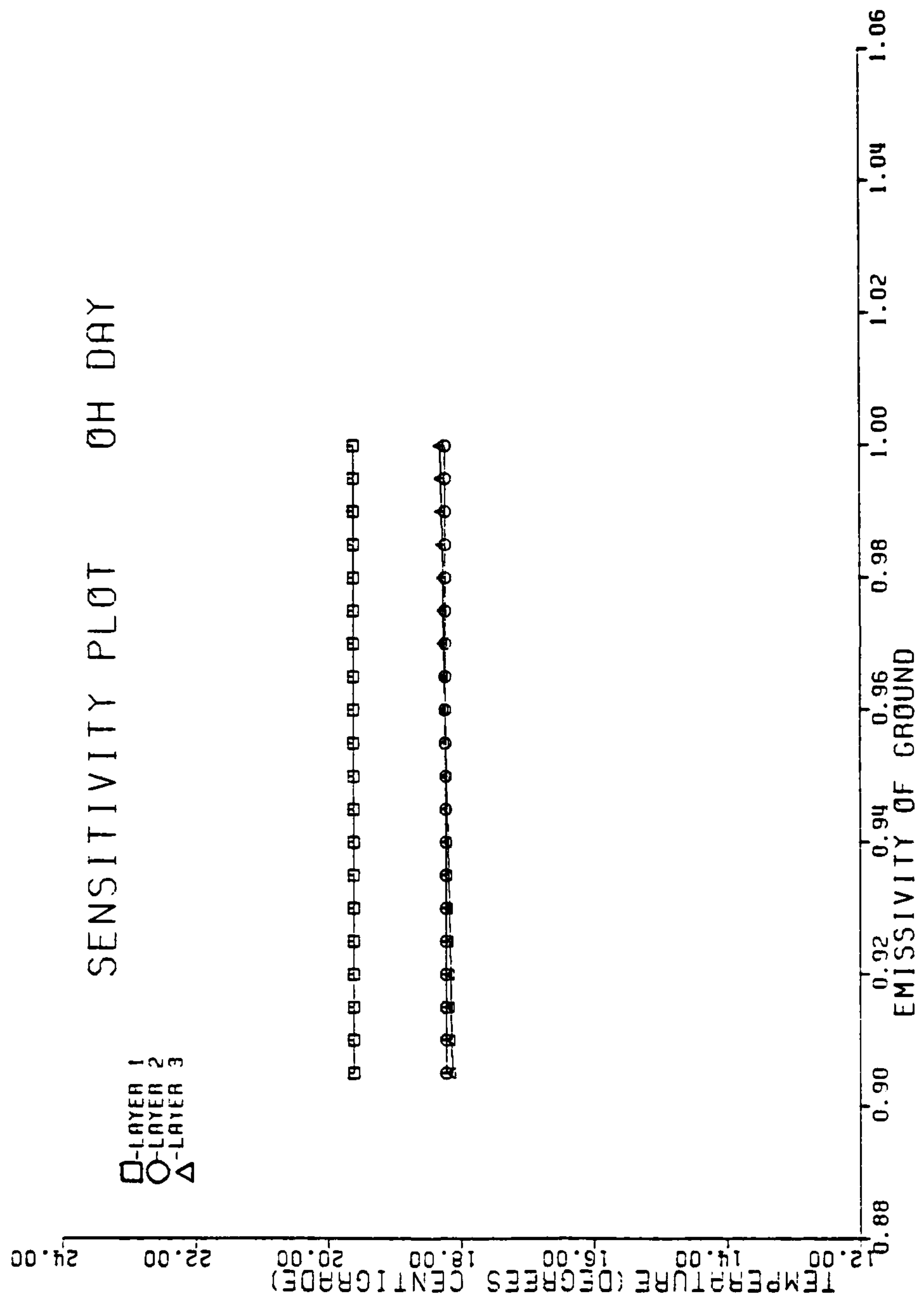

SENSITIVITY PLOT OF DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
SHORT WAVE ABSORPTION LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
0.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00

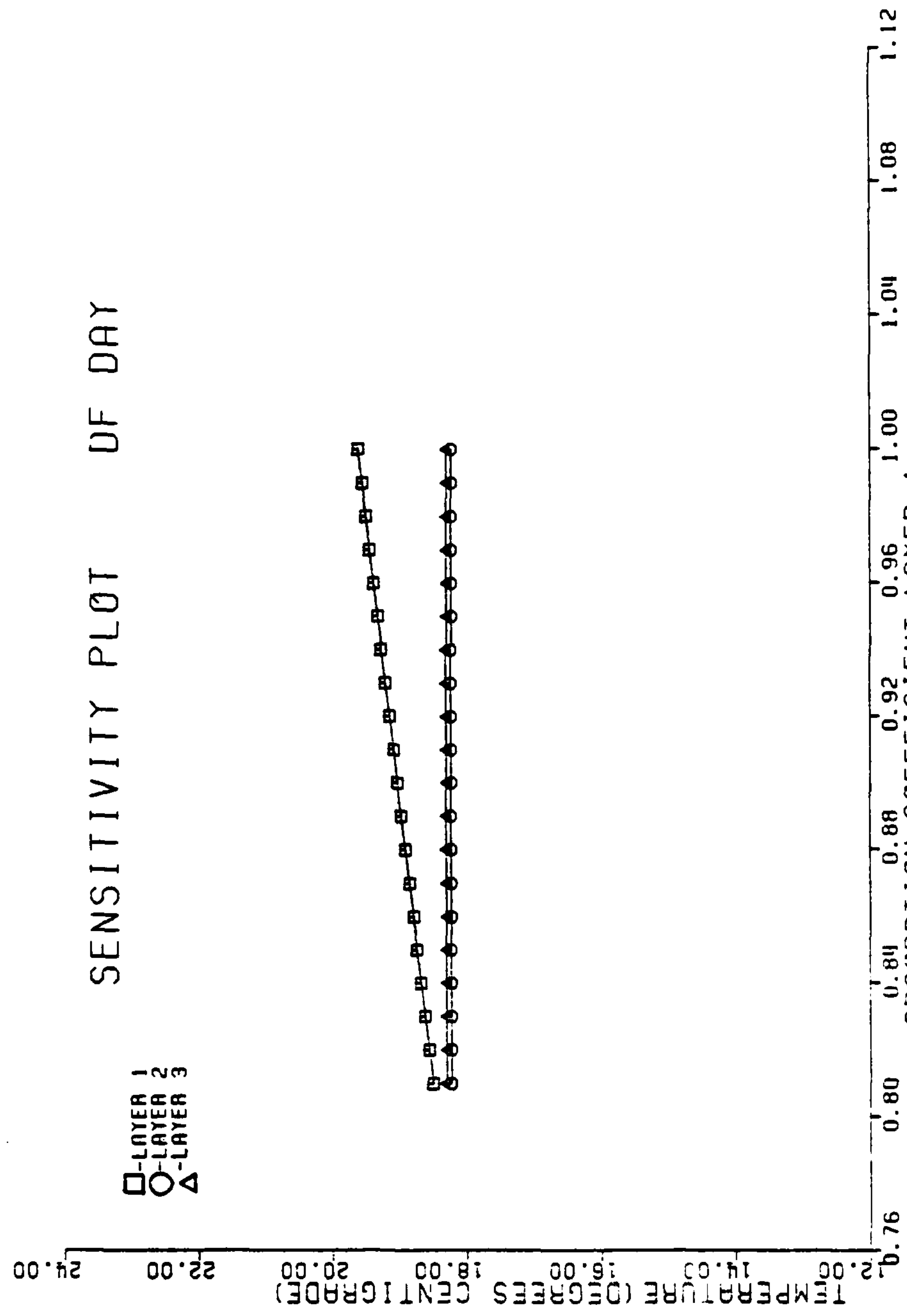


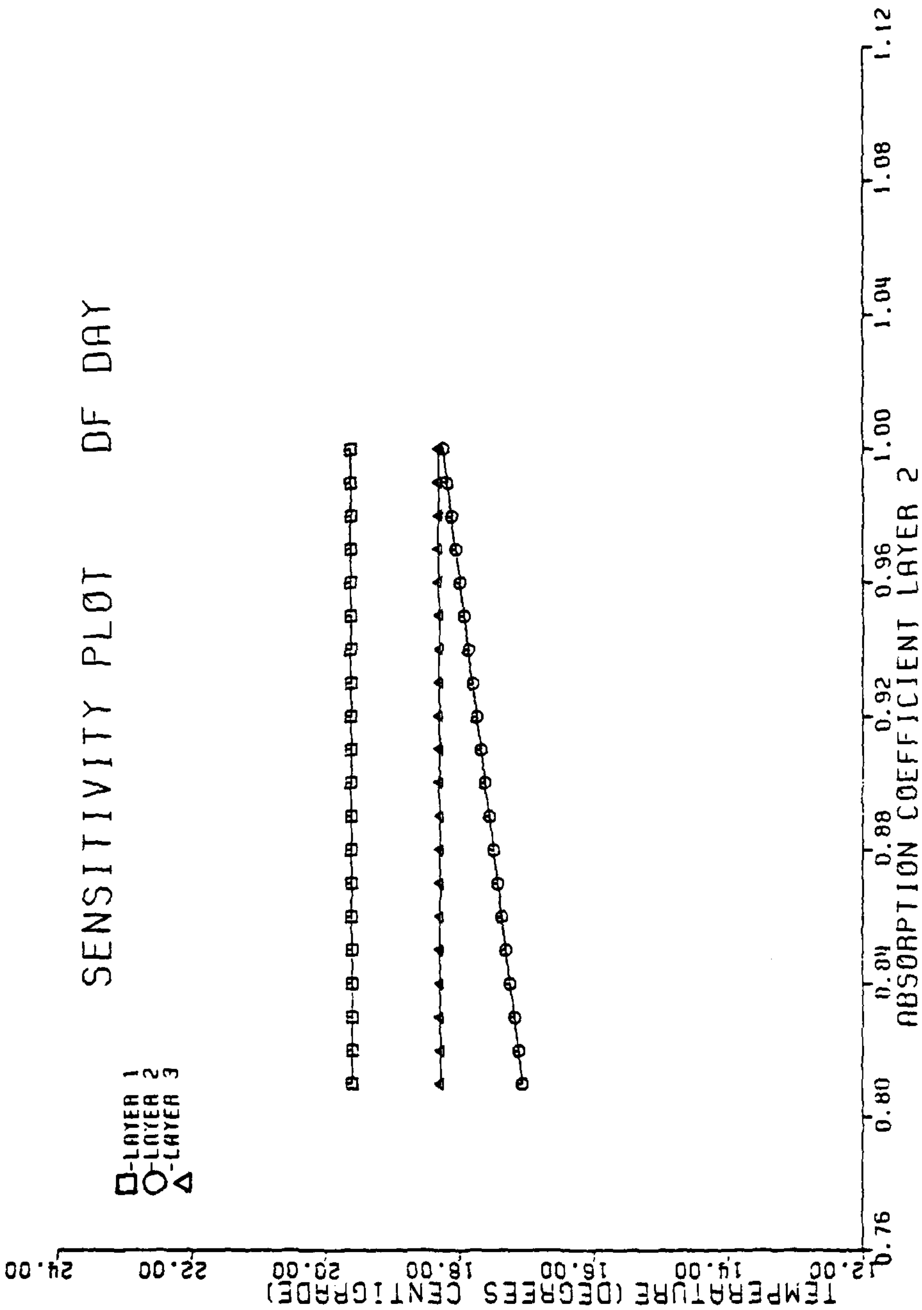
SENSITIVITY PLOT OF DAY
LAYER 1
LAYER 2
LAYER 3
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06
EMISSIVITY LAYER 1
12.00
14.00
16.00
18.00
20.00
22.00
24.00
TEMPERATURE (DEGREES CENTIGRADE)


SENSITIVITY PLØT OF DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
EMISSIVITY LAYER 2
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00

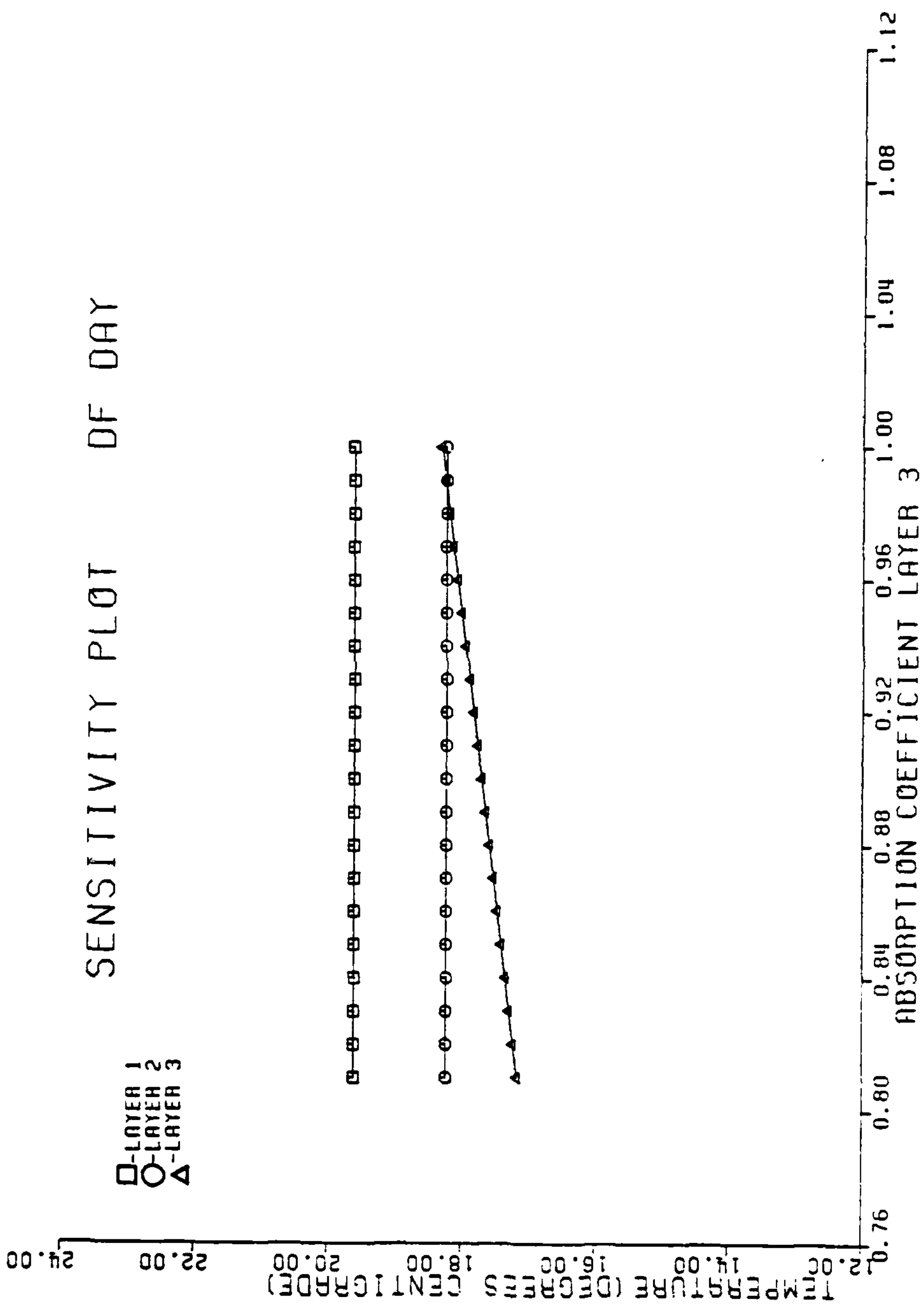

SENSITIVITY PLØT OF DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00
EMISSIVITY LAYER 3
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06


SENSITIVITY PLOT ØH DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
EMISSIVITY ØF GRØUND
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00

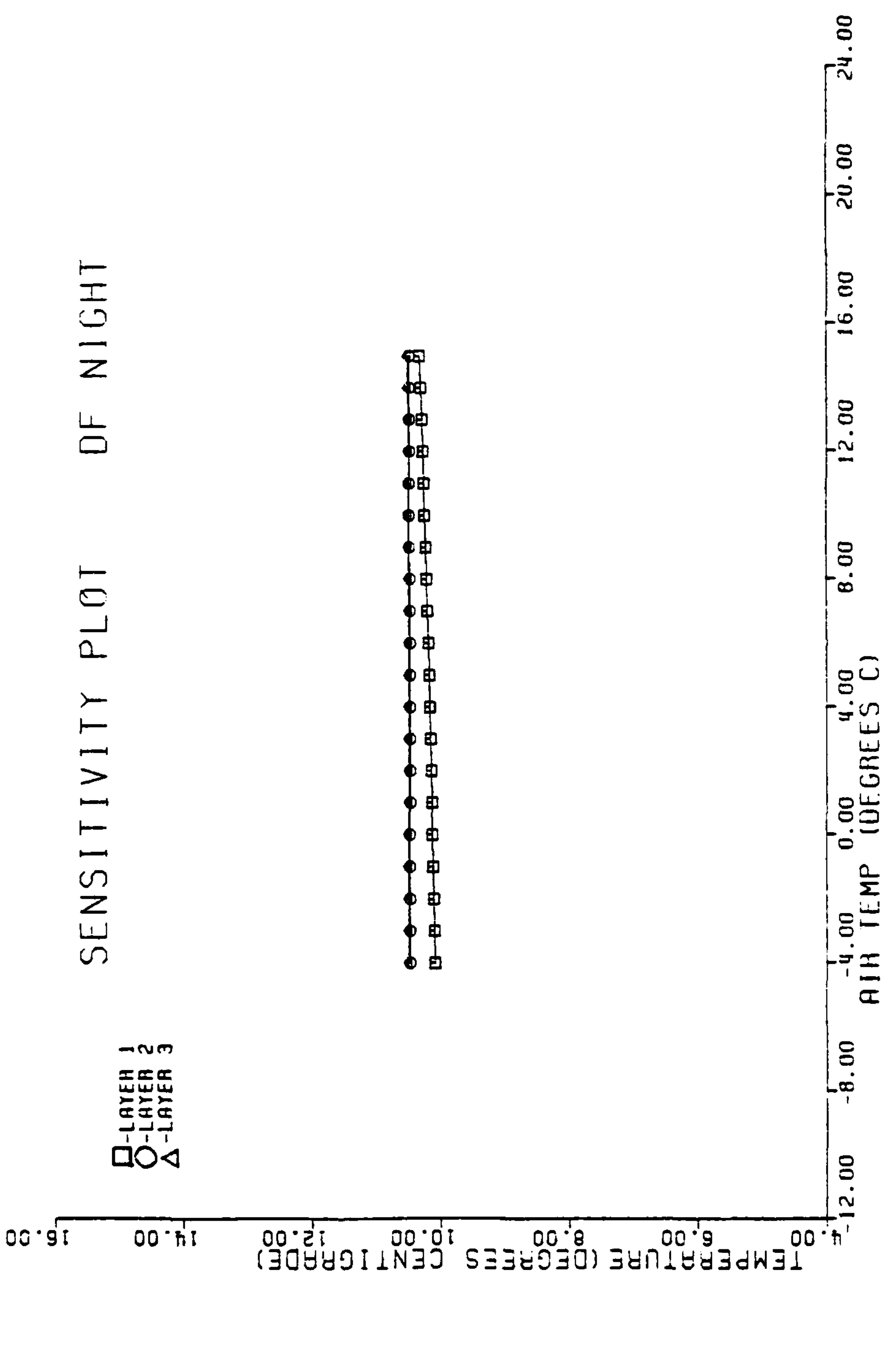

SENSITIVITY PLØT OF DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
0.76
0.80
0.84
0.88
0.92
0.96
1.00
1.04
1.08
1.12
ABSØRPTIØN CØEFFICIENT LAYER 1
12.00
14.00
16.00
18.00
20.00
22.00
24.00
TEMPERATURE (DEGREES CENTIGRADE)



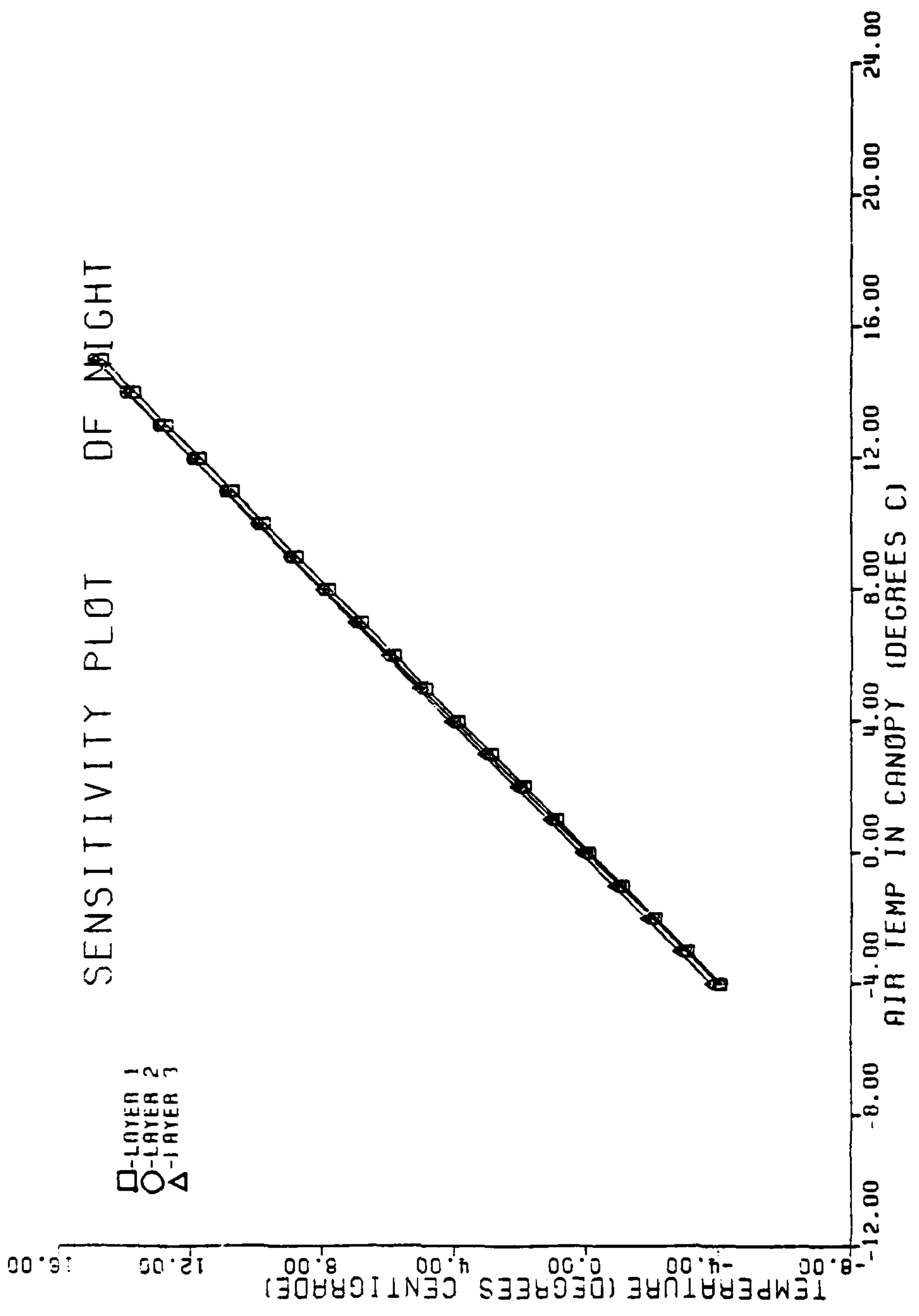
SENSITIVITY PLØT OF DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
ABSORPTION COEFFICIENT LAYER 2
0.76
0.80
0.84
0.88
0.92
0.96
1.00
1.04
1.08
1.12
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00

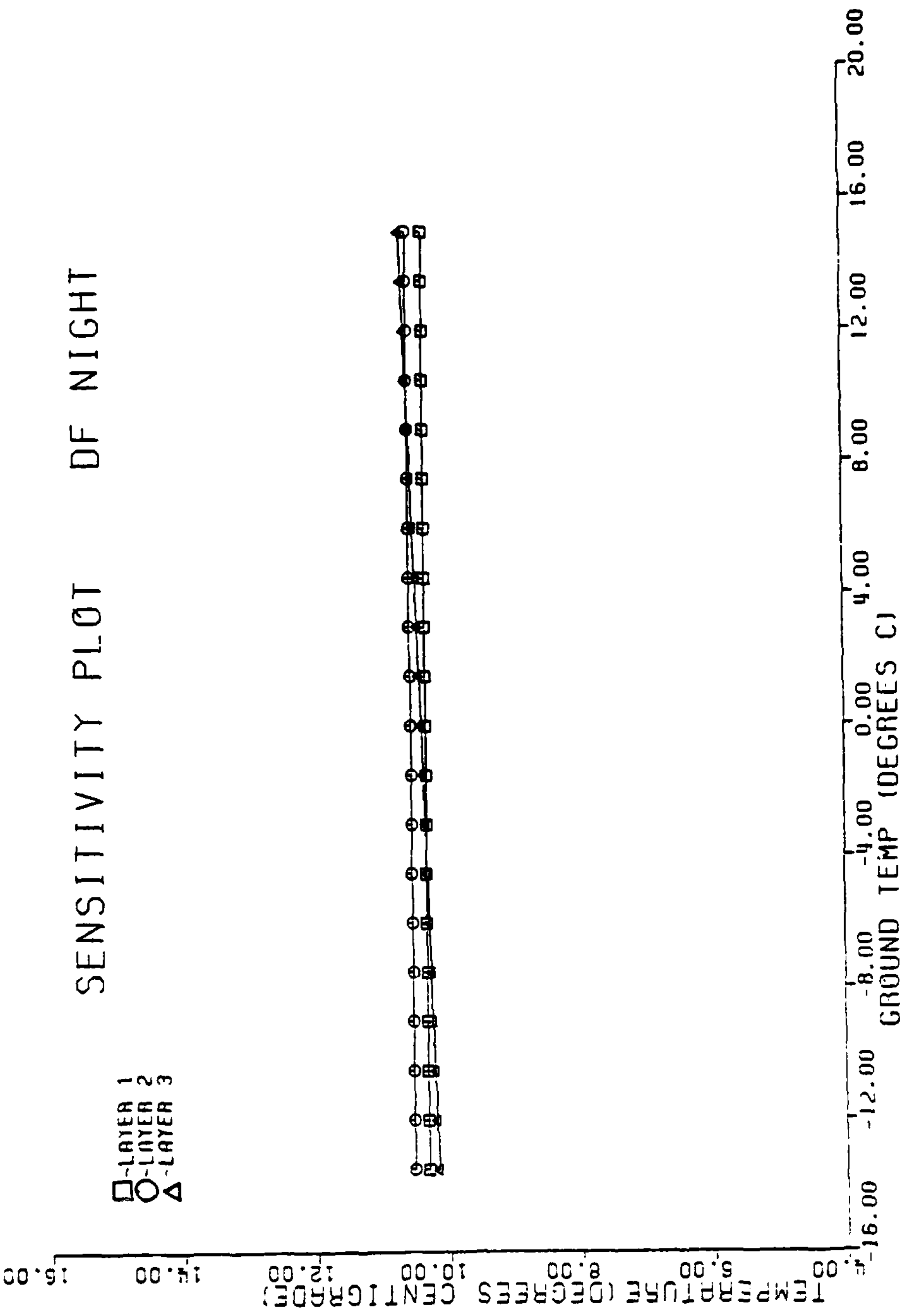

SENSITIVITY PLOT OF DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
ABSORPTION COEFFICIENT LAYER 3
0.76
0.80
0.84
0.88
0.92
0.96
1.00
1.04
1.08
1.12
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00

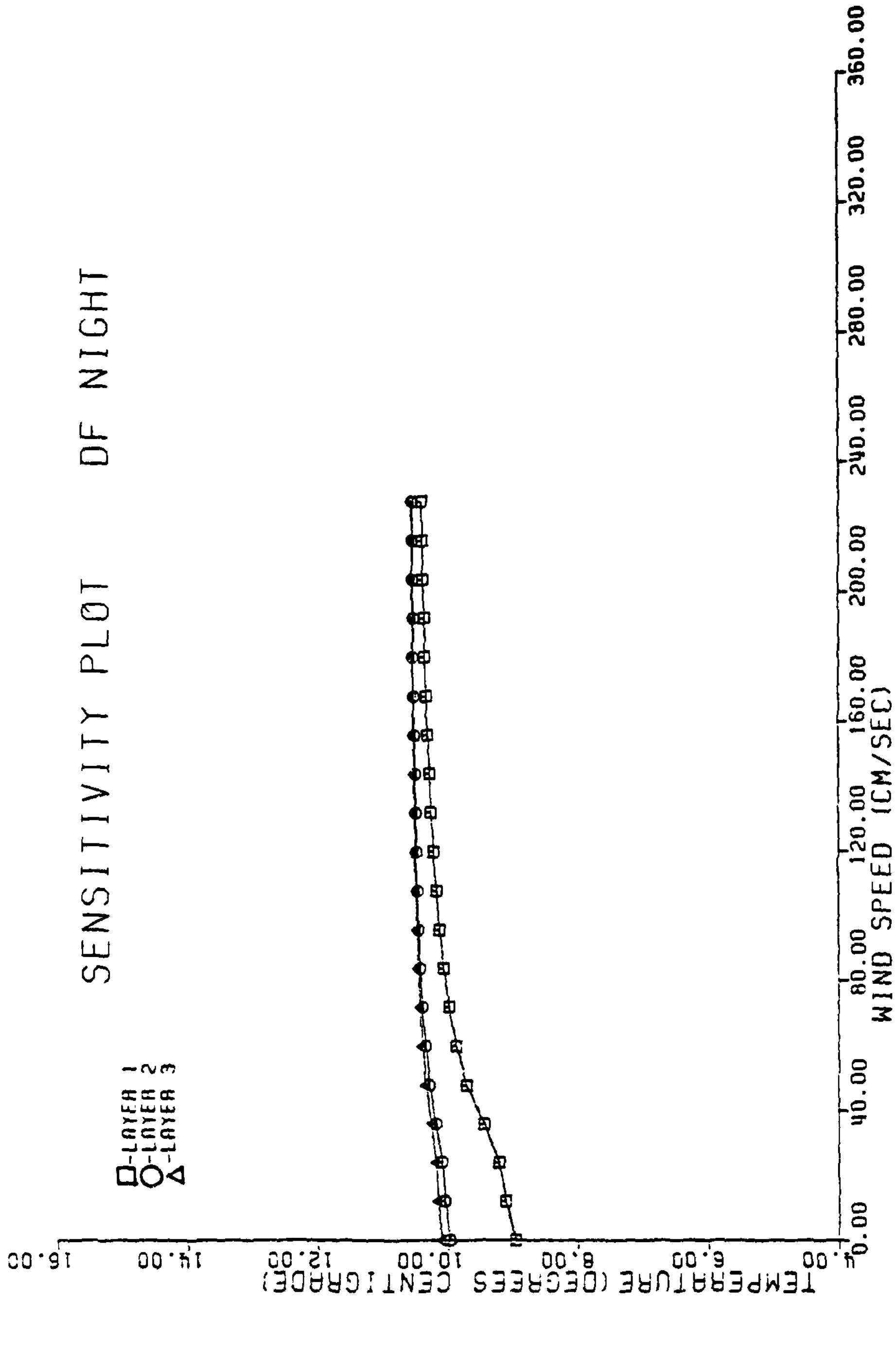
Douglas-Fir Nighttime Sensitivity Plots

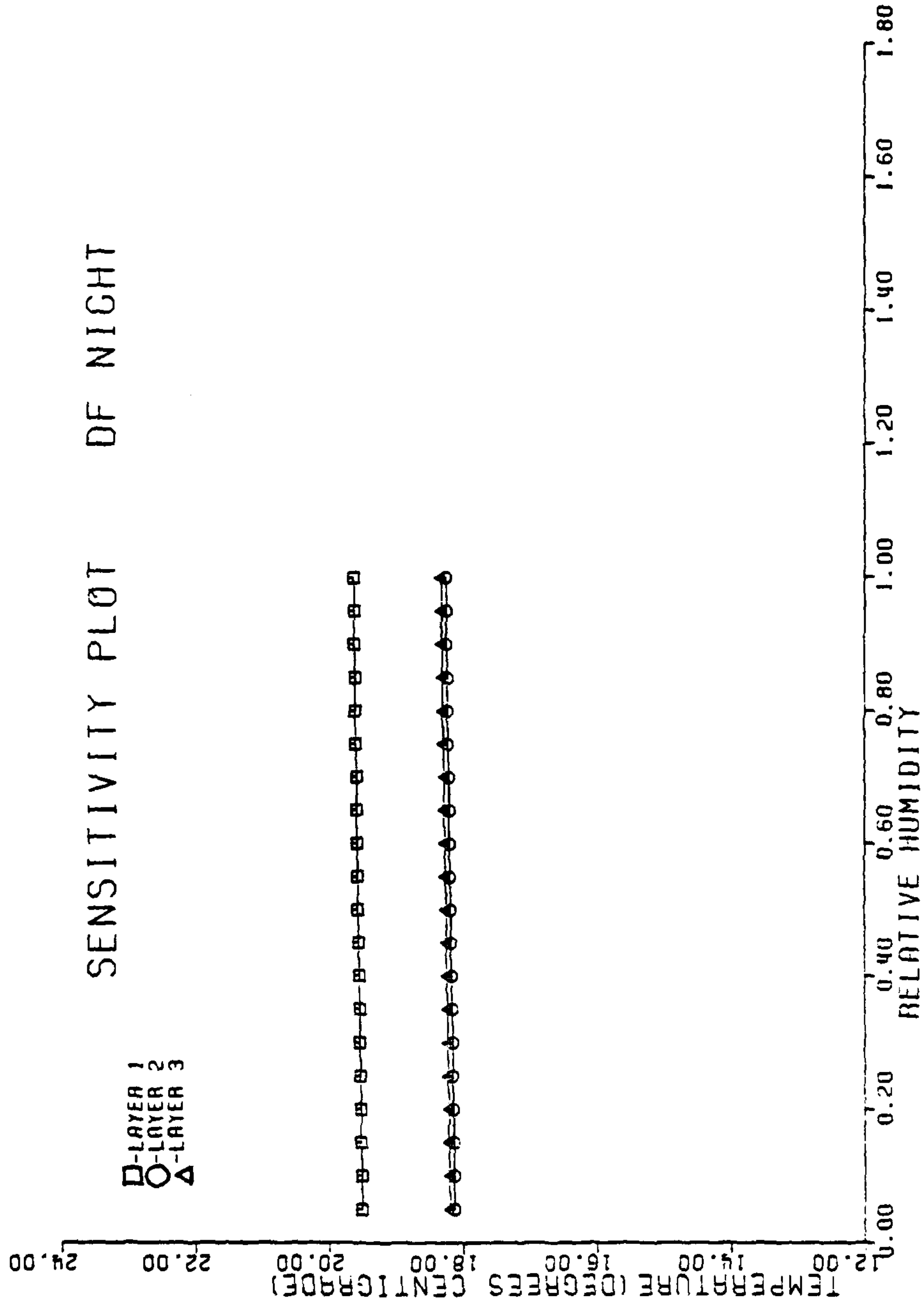


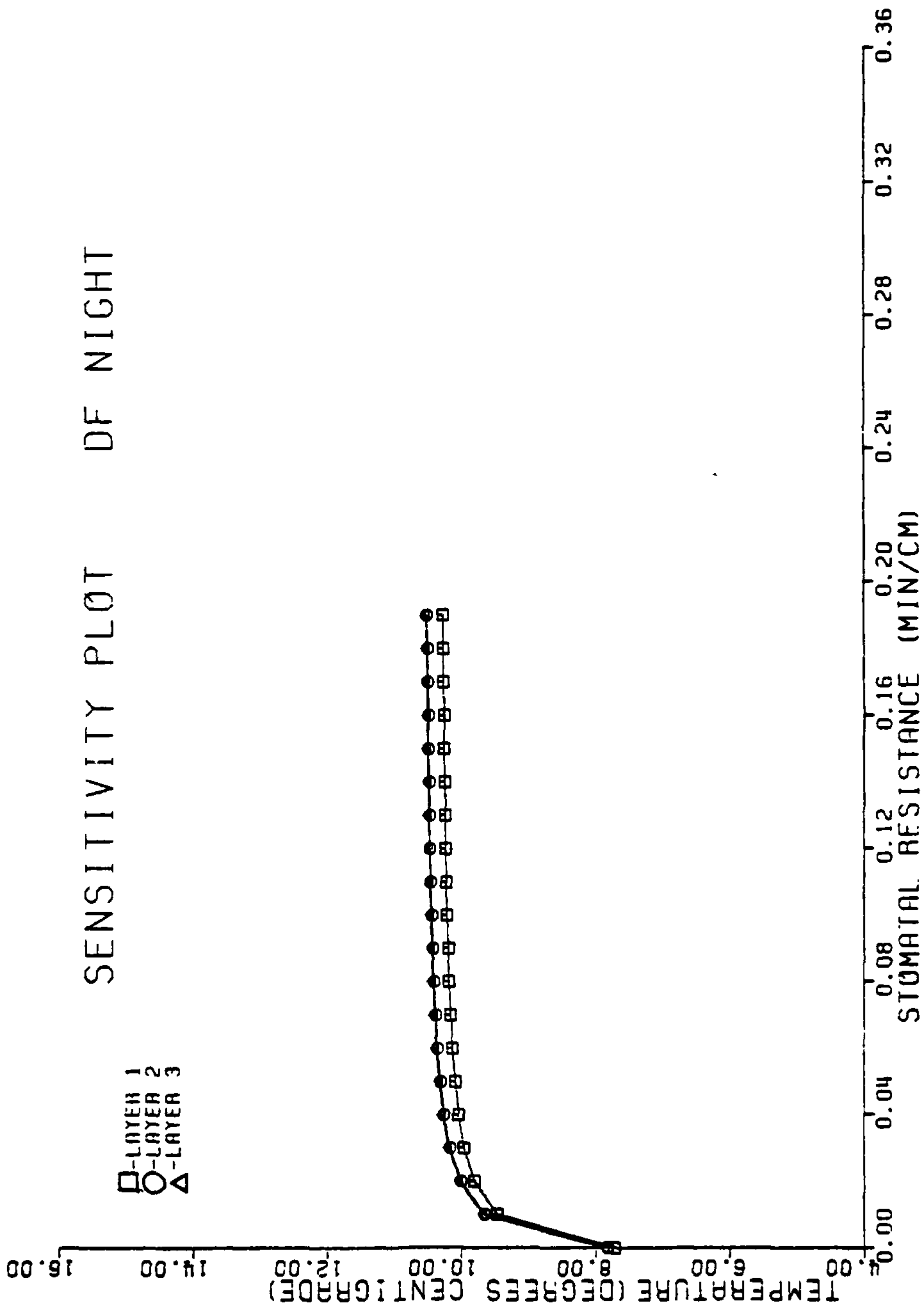
SENSITIVITY PLOT OF NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
AIR TEMP (DEGREES C)
TEMPERATURE (DEGREES CENTIGRADE)
-12.00
-8.00
-4.00
0.00
4.00
8.00
12.00
16.00
20.00
24.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00


SENSITIVITY PLOT OF NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
AIR TEMP IN CANOPY (DEGREES C)
-12.00
-8.00
-4.00
0.00
4.00
8.00
12.00
16.00
20.00
24.00
TEMPERATURE (DEGREES CENTIGRADE)
-8.00
-4.00
0.00
4.00
8.00
12.00
16.00

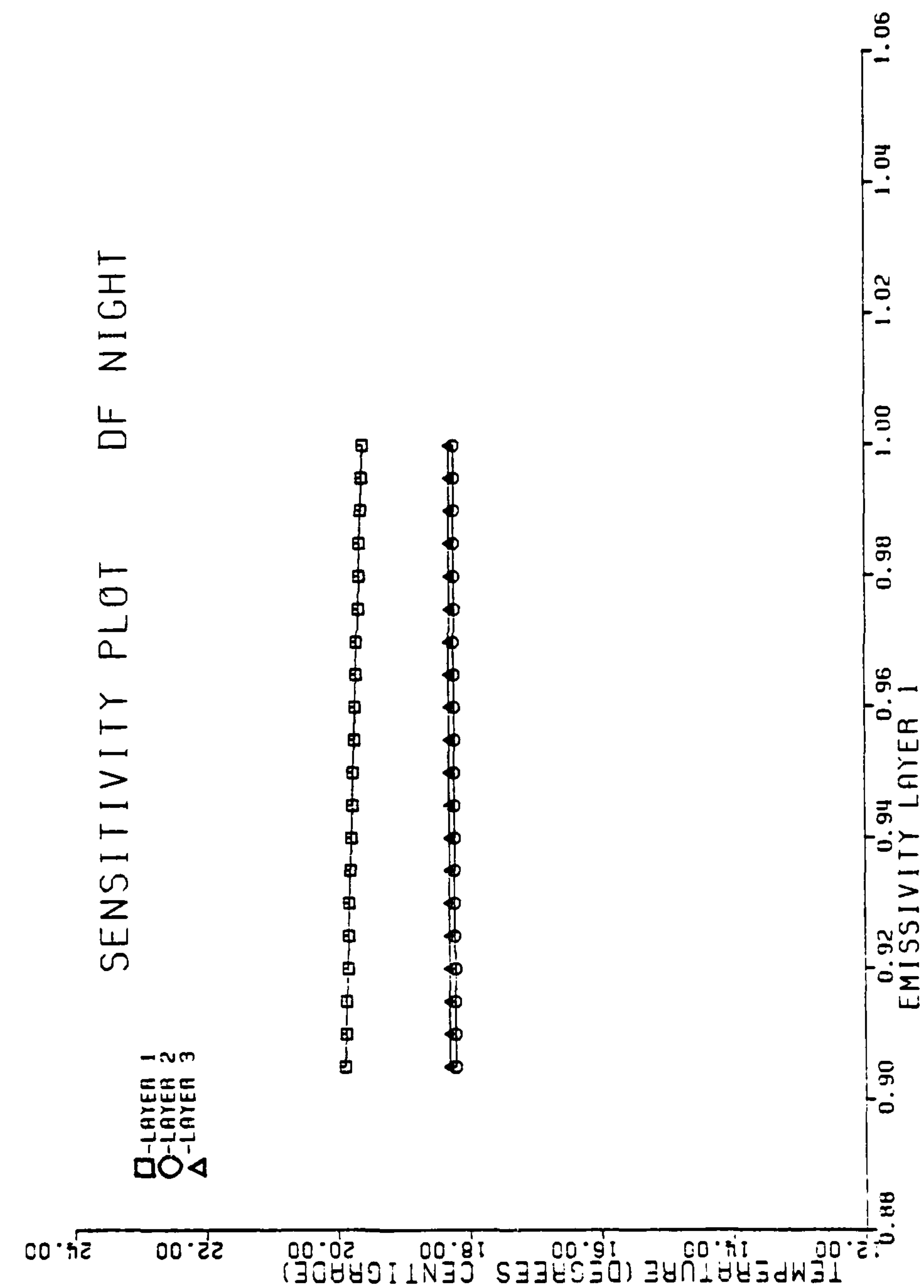

SENSITIVITY PLOT DF NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
GROUND TEMP (DEGREES C)
-16.00
-12.00
-8.00
-4.00
0.00
4.00
8.00
12.00
16.00
20.00
TEMPERATURE (DEGREES CENTIGRADE)
4.00
6.00
8.00
10.00
12.00
14.00
16.00

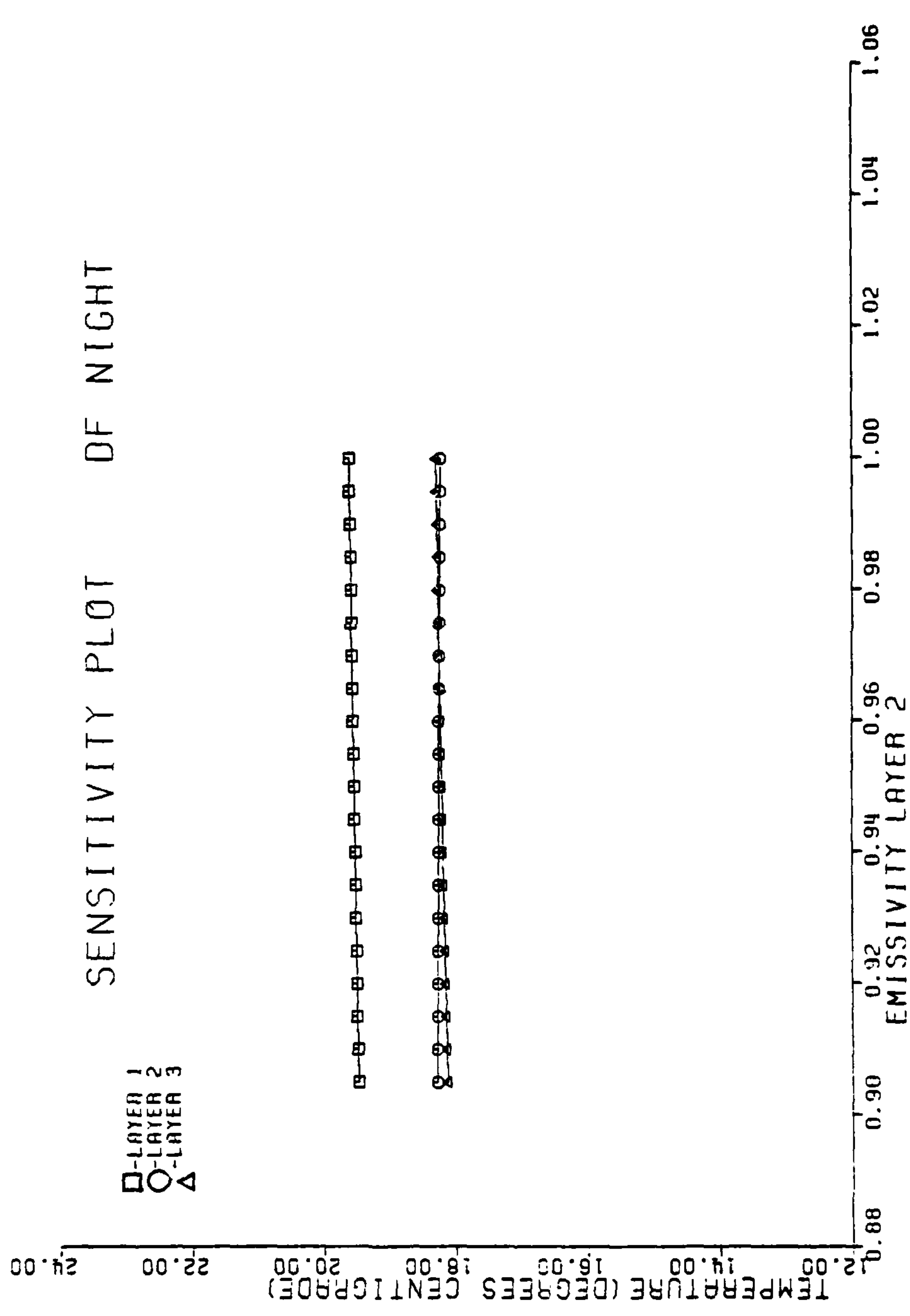

SENSITIVITY PLOT DF NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
WIND SPEED (CM/SEC)
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280.00
320.00
360.00
TEMPERATURE (DEGREES CENTIGRADE)
4.00
6.00
8.00
10.00
12.00
14.00
16.00

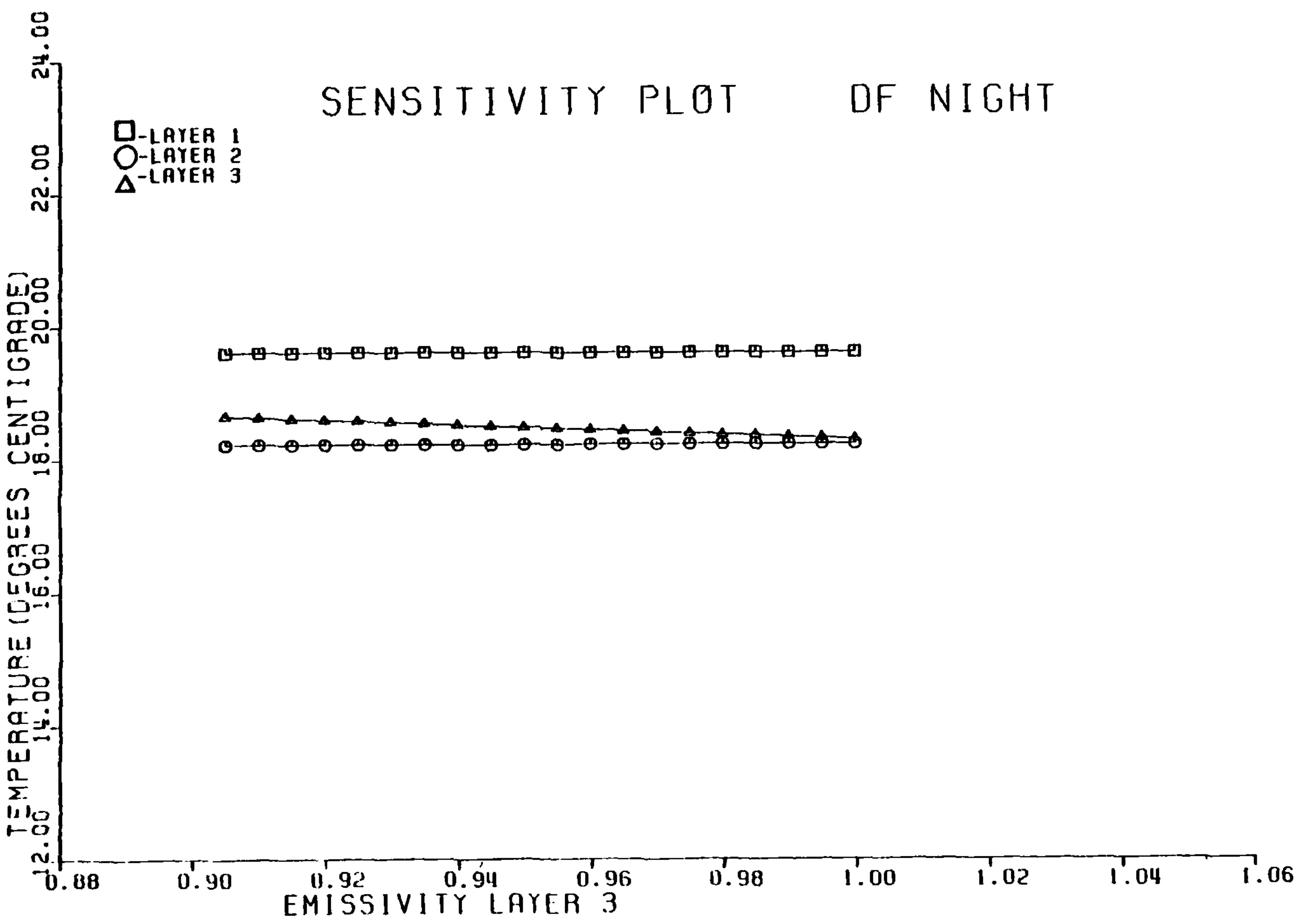

SENSITIVITY PLOT DF NIGHT
-LAYER 1
-LAYER 2
-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00
RELATIVE HUMIDITY
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80



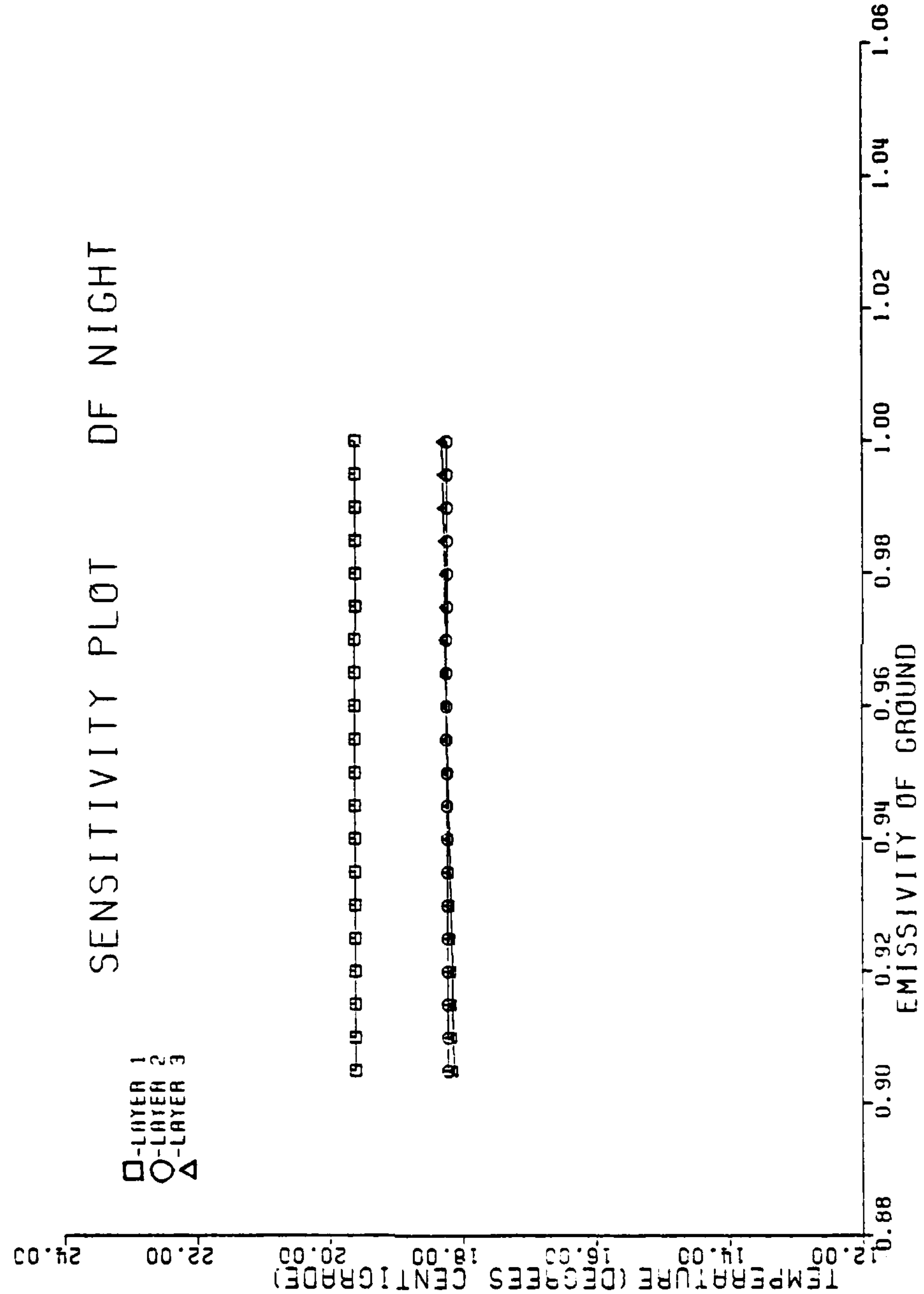
SENSITIVITY PLØT DF NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
4.00
6.00
8.00
10.00
12.00
14.00
16.00
STOMATAL RESISTANCE (MIN/CM)
0.00
0.04
0.08
0.12
0.16
0.20
0.24
0.28
0.32
0.36

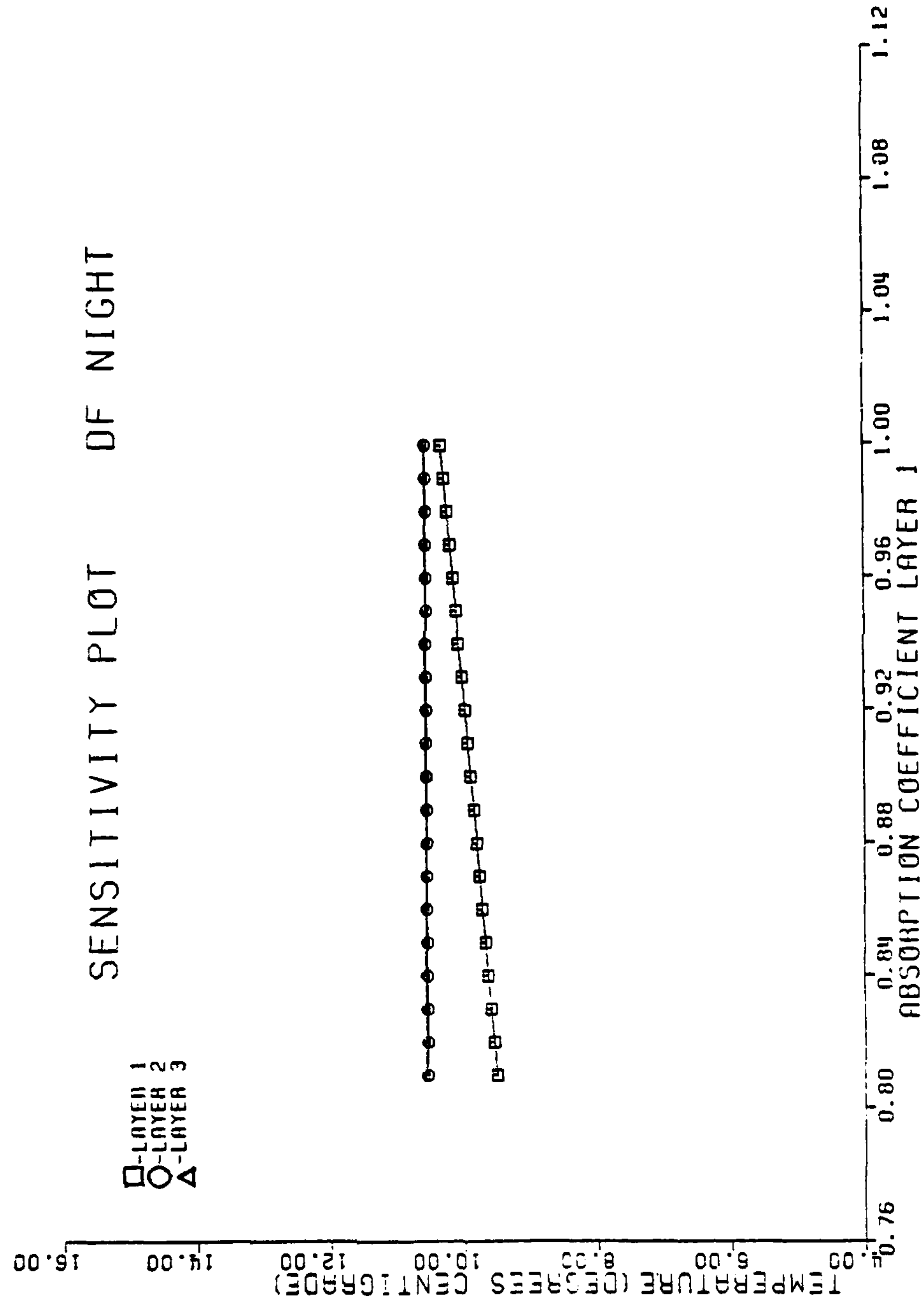

SENSITIVITY PLOT DF NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
EMISSIVITY LAYER 1
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00


SENSITIVITY PLOT OF NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
EMISSIVITY LAYER 2
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00

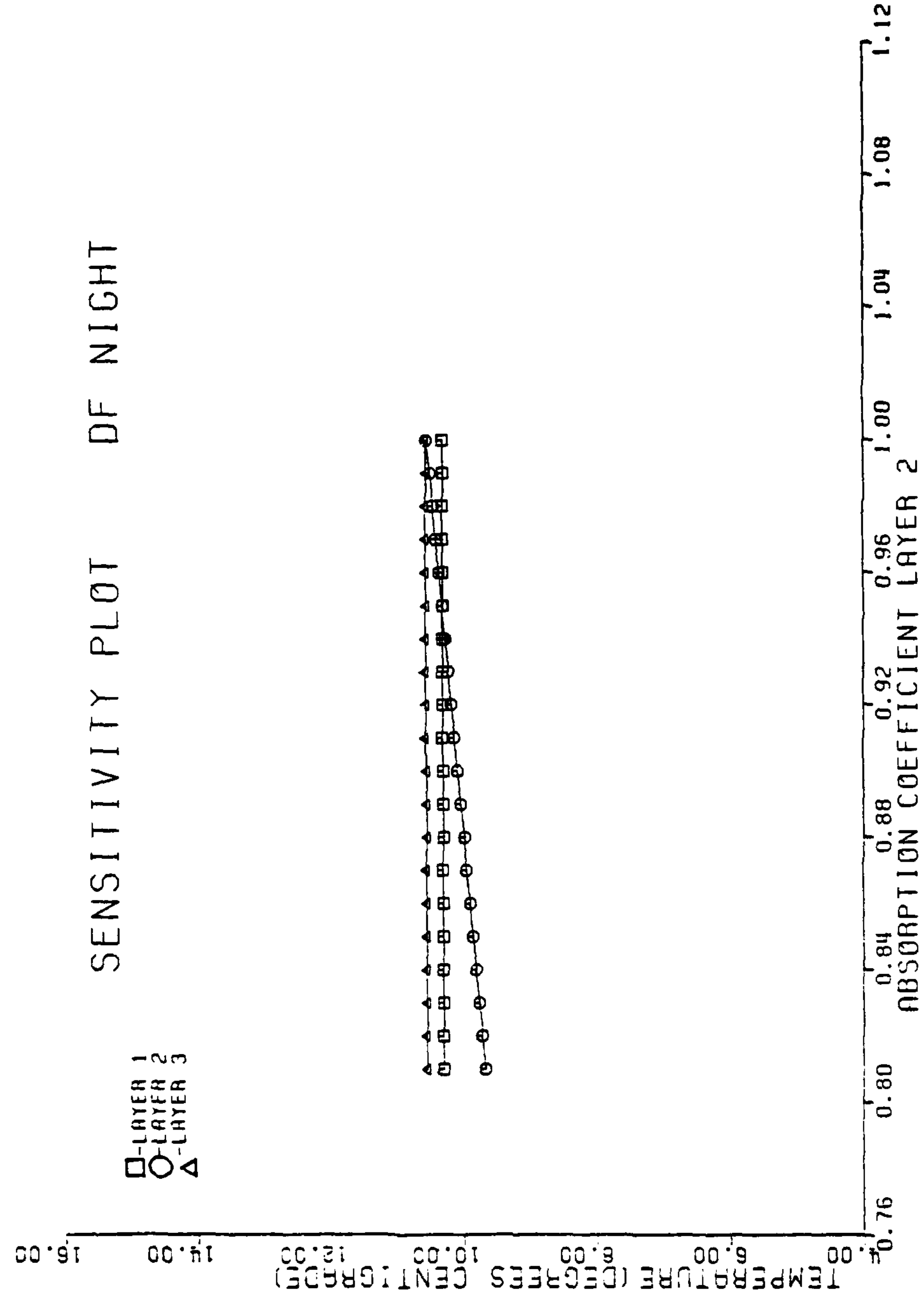


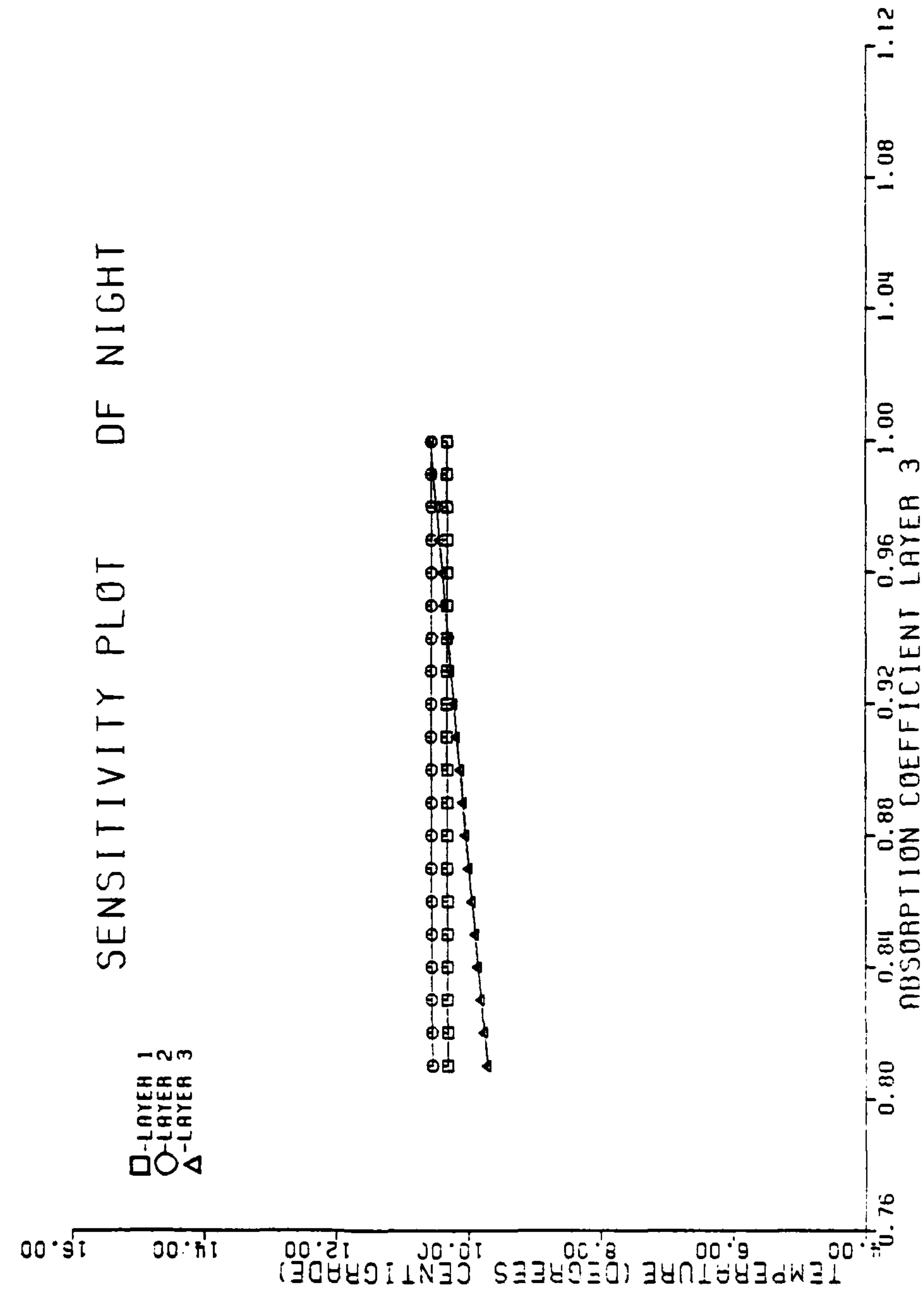
SENSITIVITY PLØT DF NIGHT
-LAYER 1
-LAYER 2
-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00
EMISSIVITY LAYER 3
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06


SENSITIVITY PLOT OF NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
EMISSIVITY OF GROUND
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00

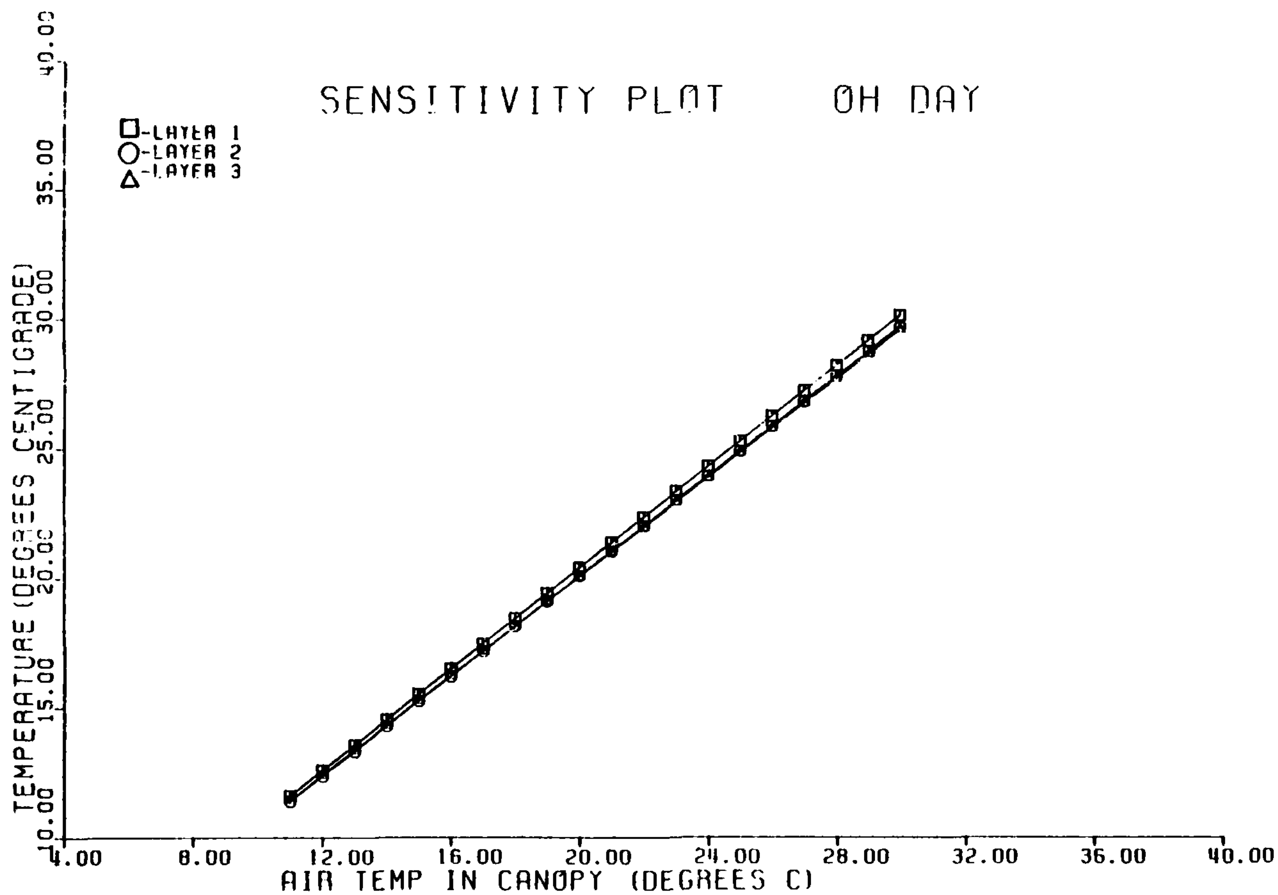


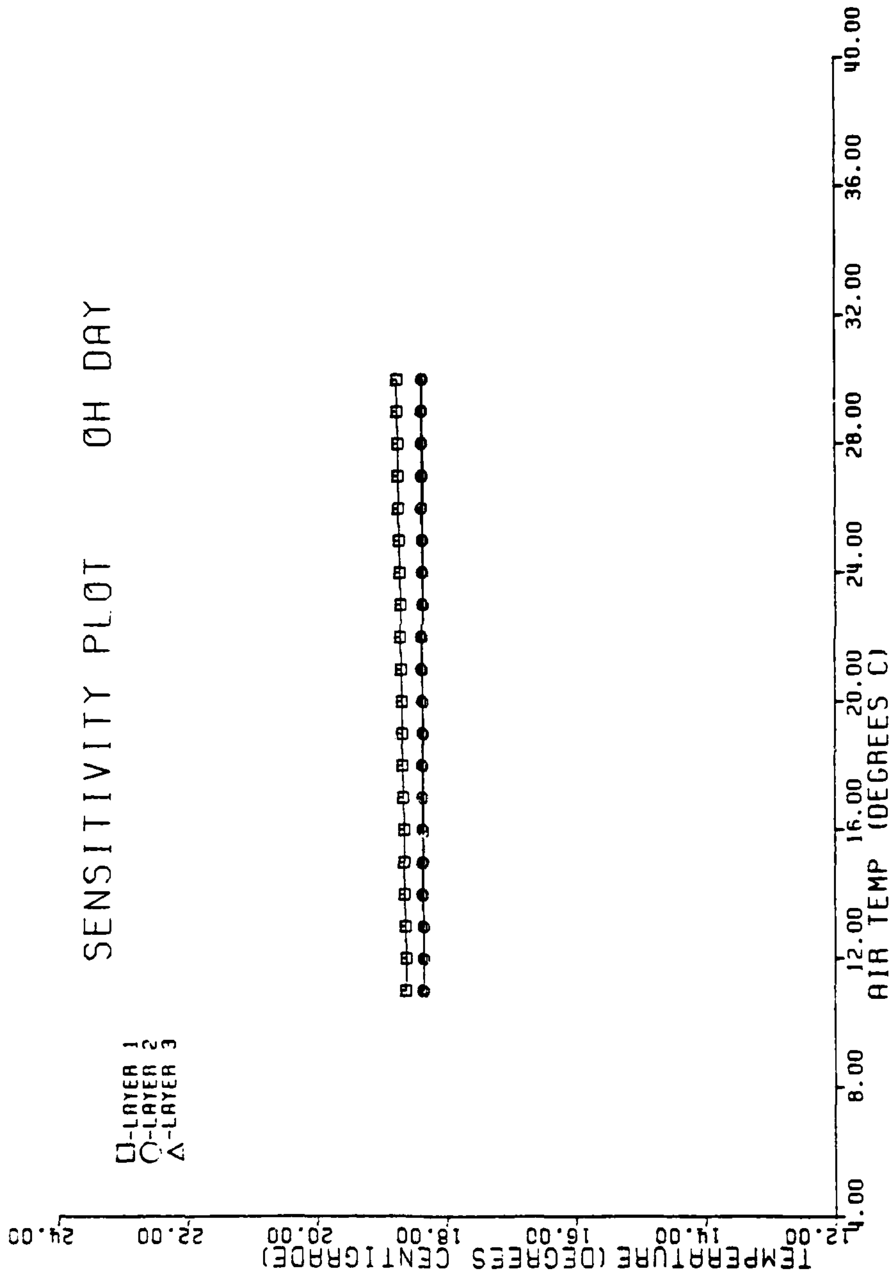
SENSITIVITY PLOT OF NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
ABSORPTION COEFFICIENT LAYER 1
0.76
0.80
0.84
0.88
0.92
0.96
1.00
1.04
1.08
1.12
TEMPERATURE (DEGREES CENTIGRADE)
4.00
6.00
8.00
10.00
12.00
14.00
16.00

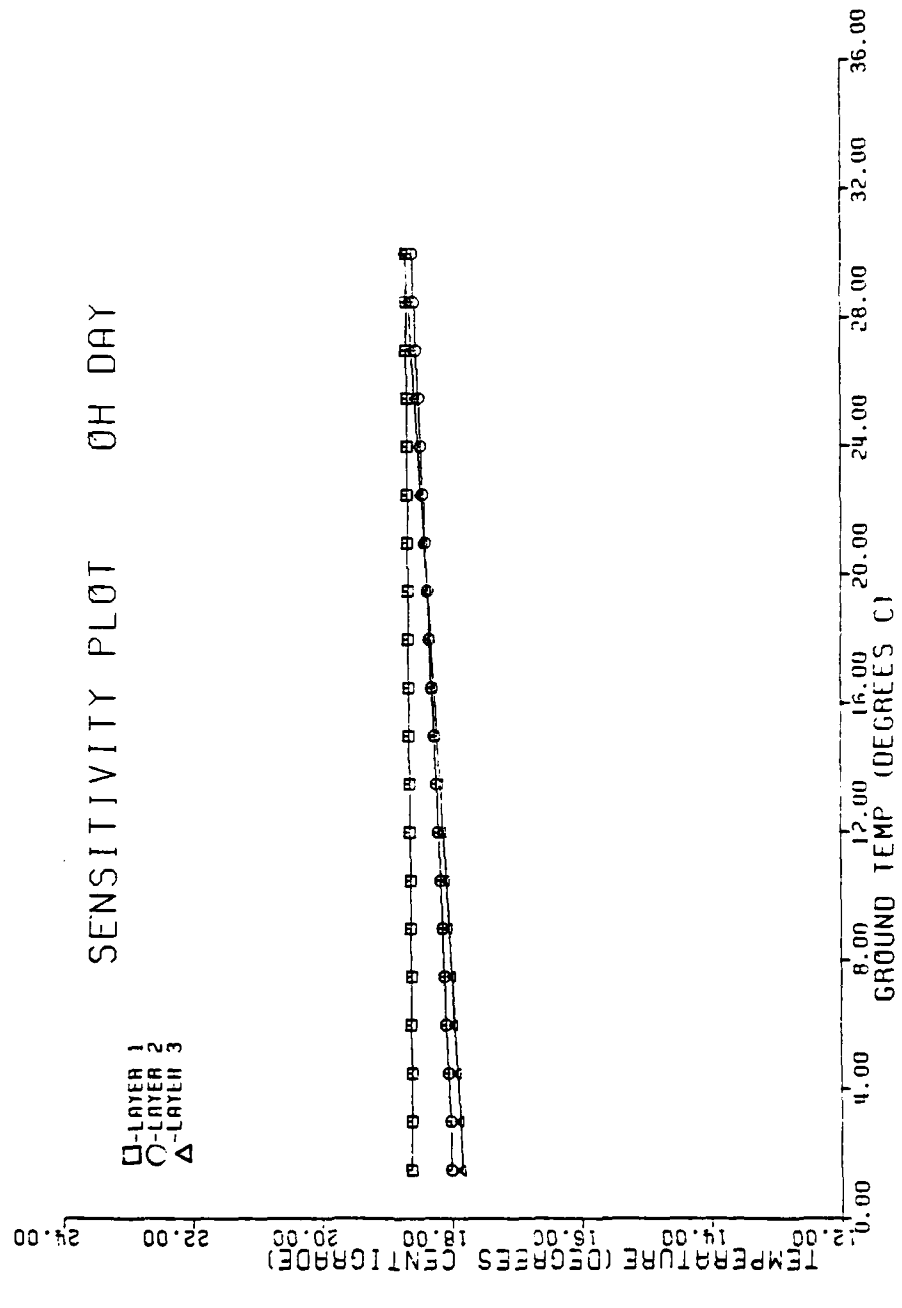

SENSITIVITY PLOT OF NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
4.00
6.00
8.00
10.00
12.00
14.00
16.00
ABSORPTION COEFFICIENT LAYER 2
0.76
0.80
0.84
0.88
0.92
0.96
1.00
1.04
1.08
1.12


SENSITIVITY PLØT ØF NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
ABSØRPTIØN COEFFICIENT LAYER 3
0.76
0.80
0.84
0.88
0.92
0.96
1.00
1.04
1.08
1.12
TEMPERATURE(DEGREES CENTIGRADE)
4.00
6.00
8.00
10.00
12.00
14.00
16.00

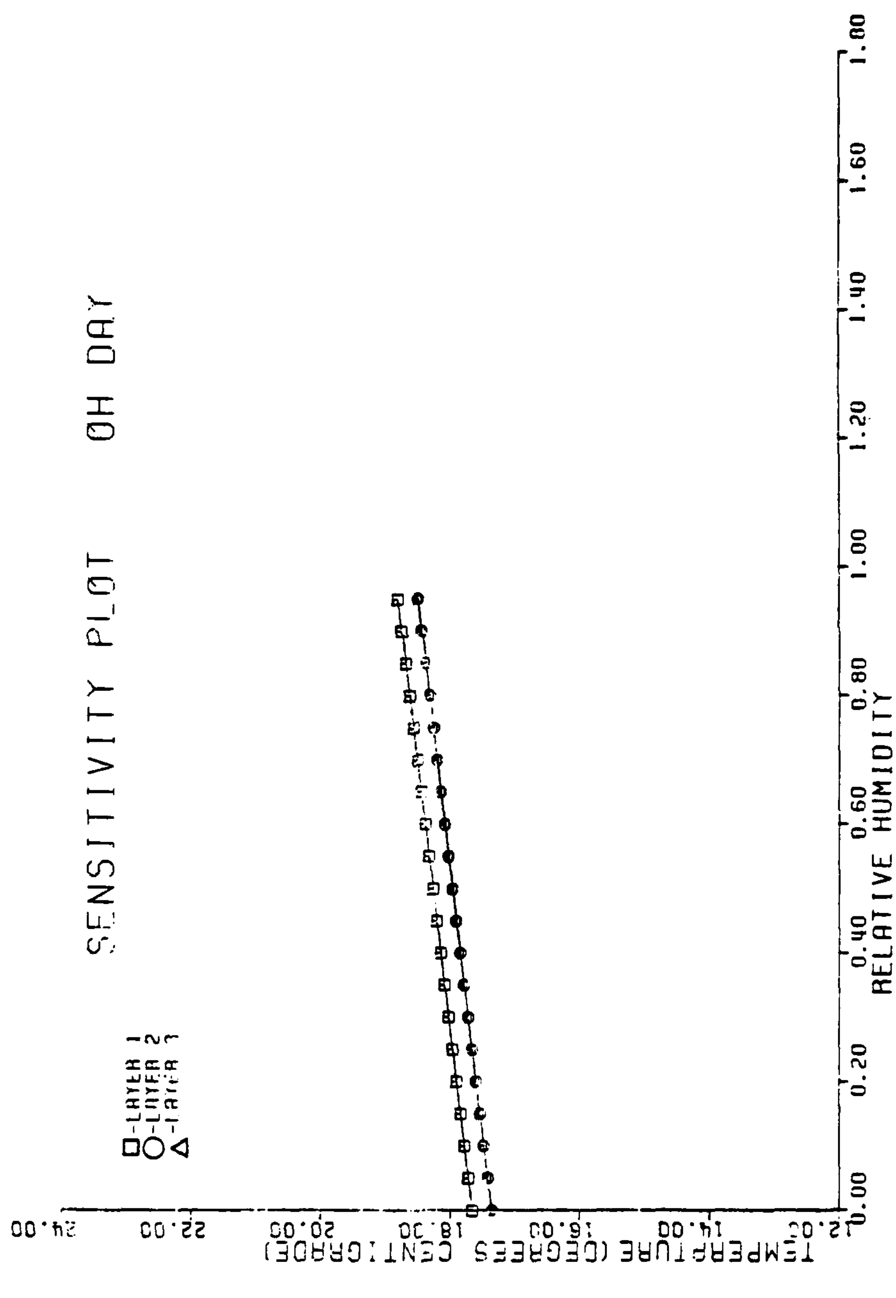
Oak-Hickory Daytime Sensitivity Plots

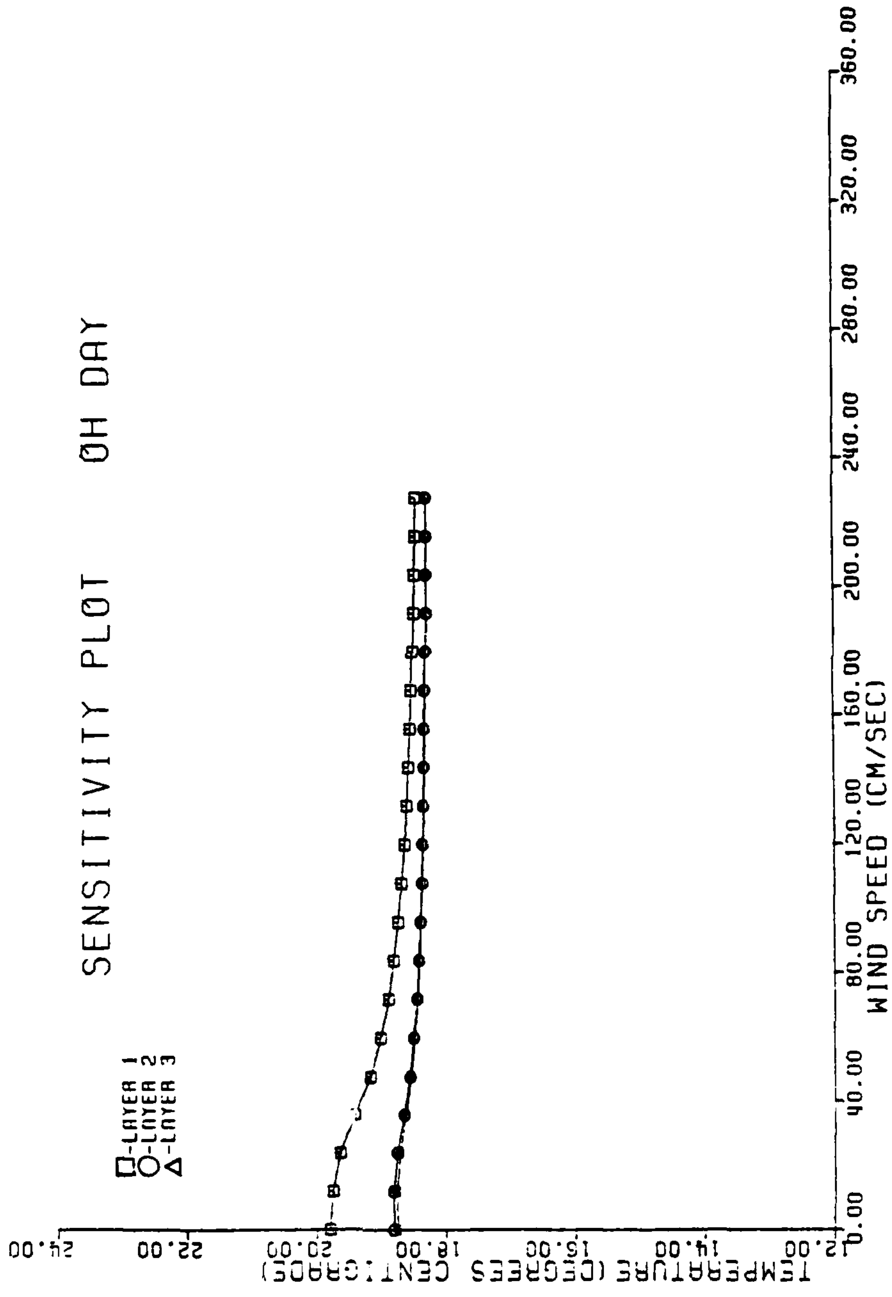

SENSITIVITY PLOT   0H DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
10.00
15.00
20.00
25.00
30.00
35.00
40.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
40.00
AIR TEMP IN CANOPY (DEGREES C)


SENSITIVITY PLOT ØH DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
AIR TEMP (DEGREES C)
TEMPERATURE (DEGREES CENTIGRADE)
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
40.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00

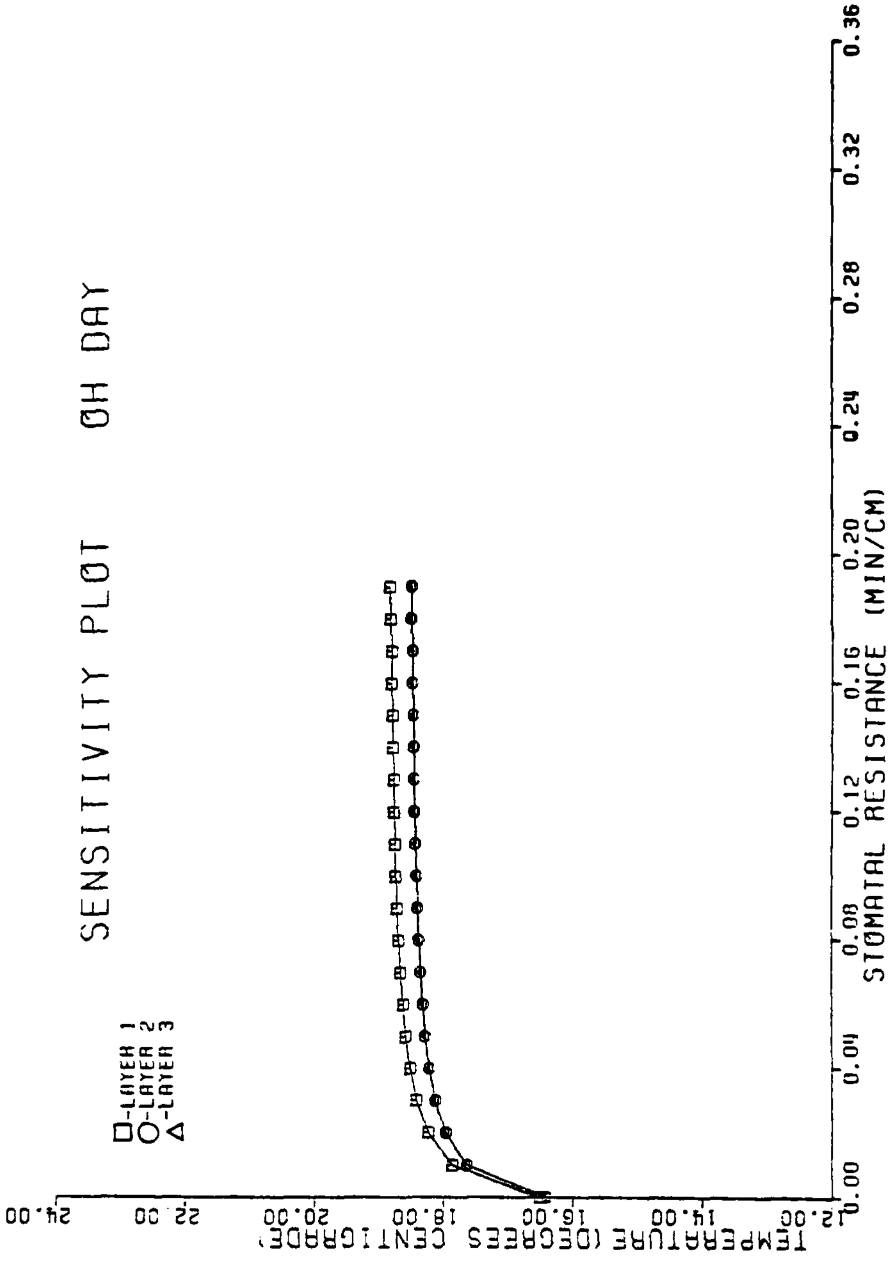


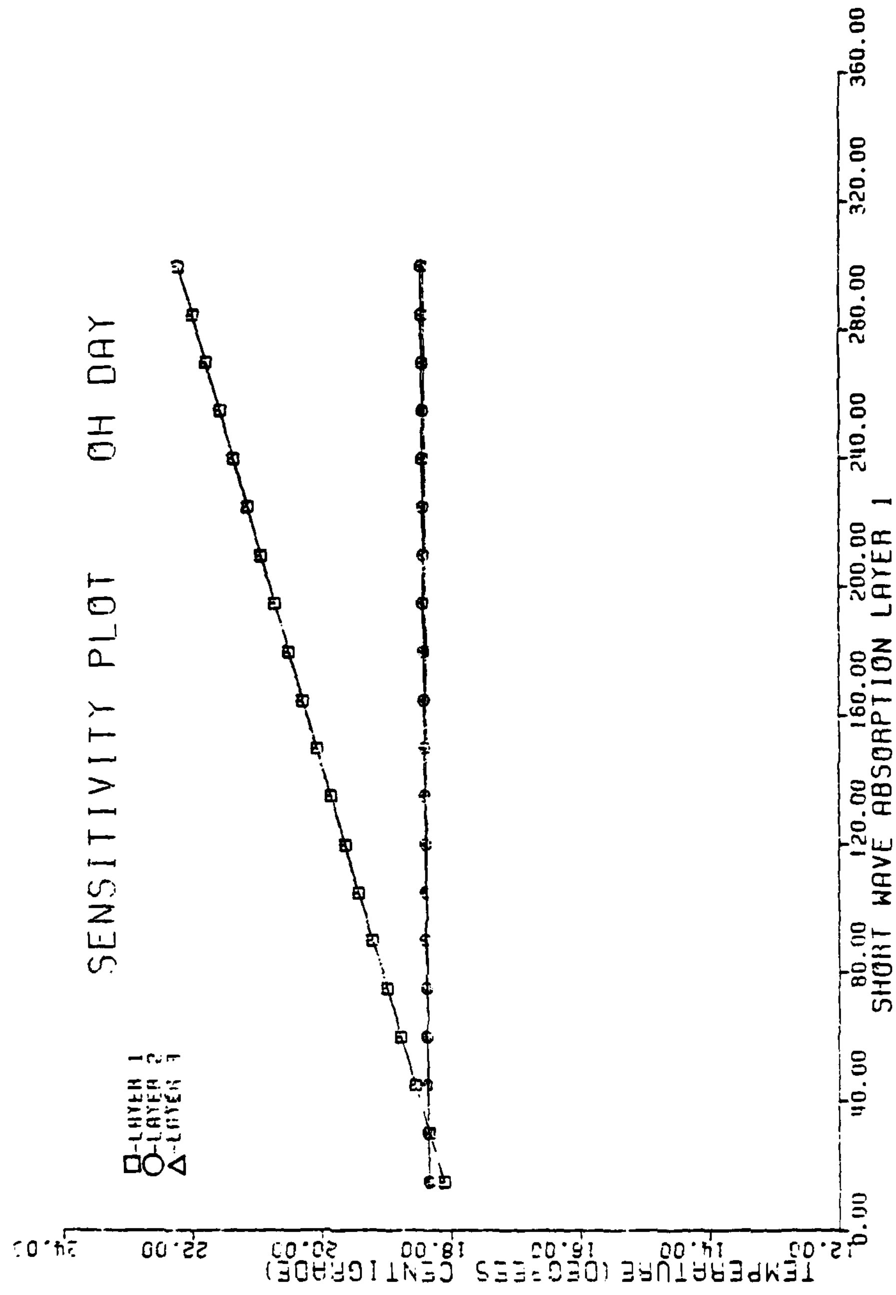
SENSITIVITY PLOT ØH DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
GROUND TEMP (DEGREES C)
0.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00


SENSITIVITY PLOT 0H DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
RELATIVE HUMIDITY
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00

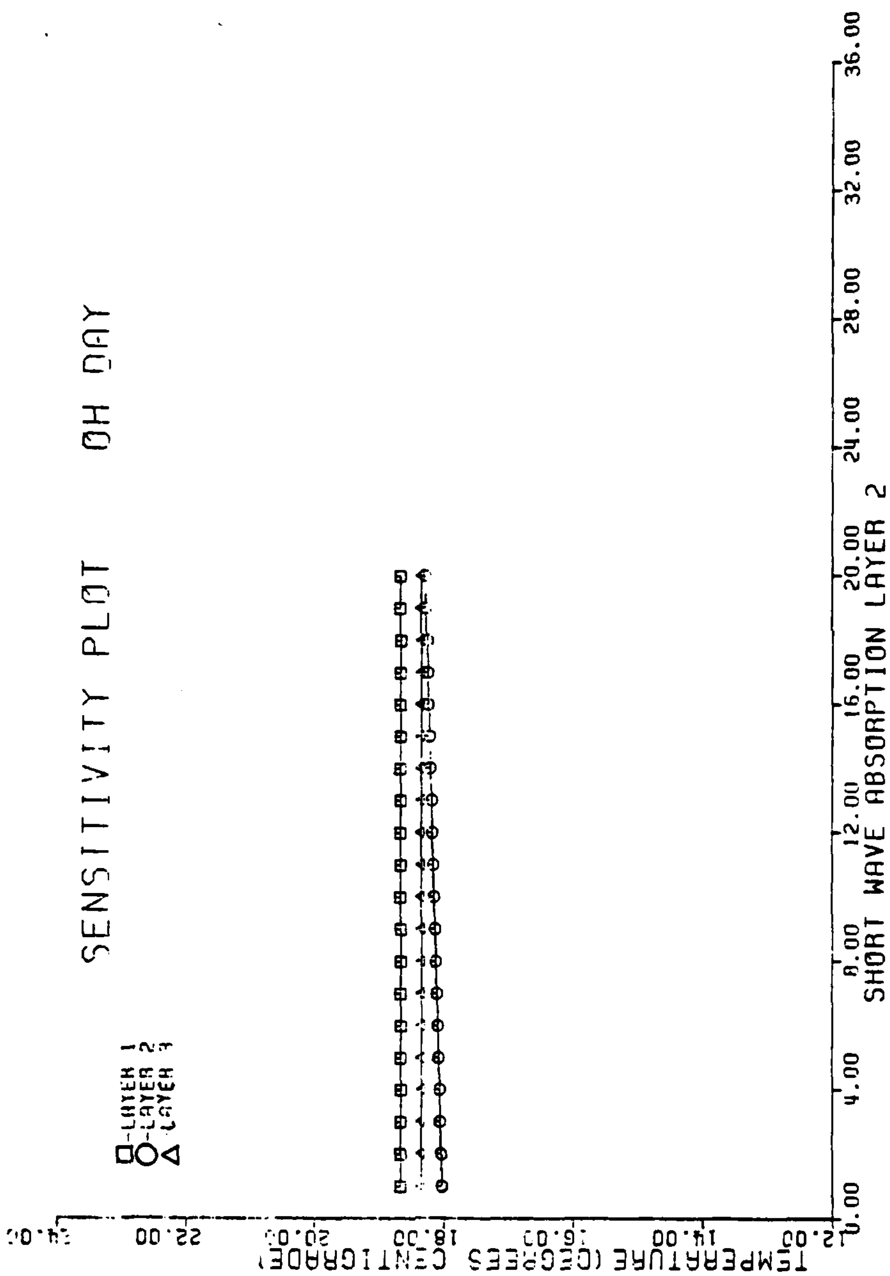


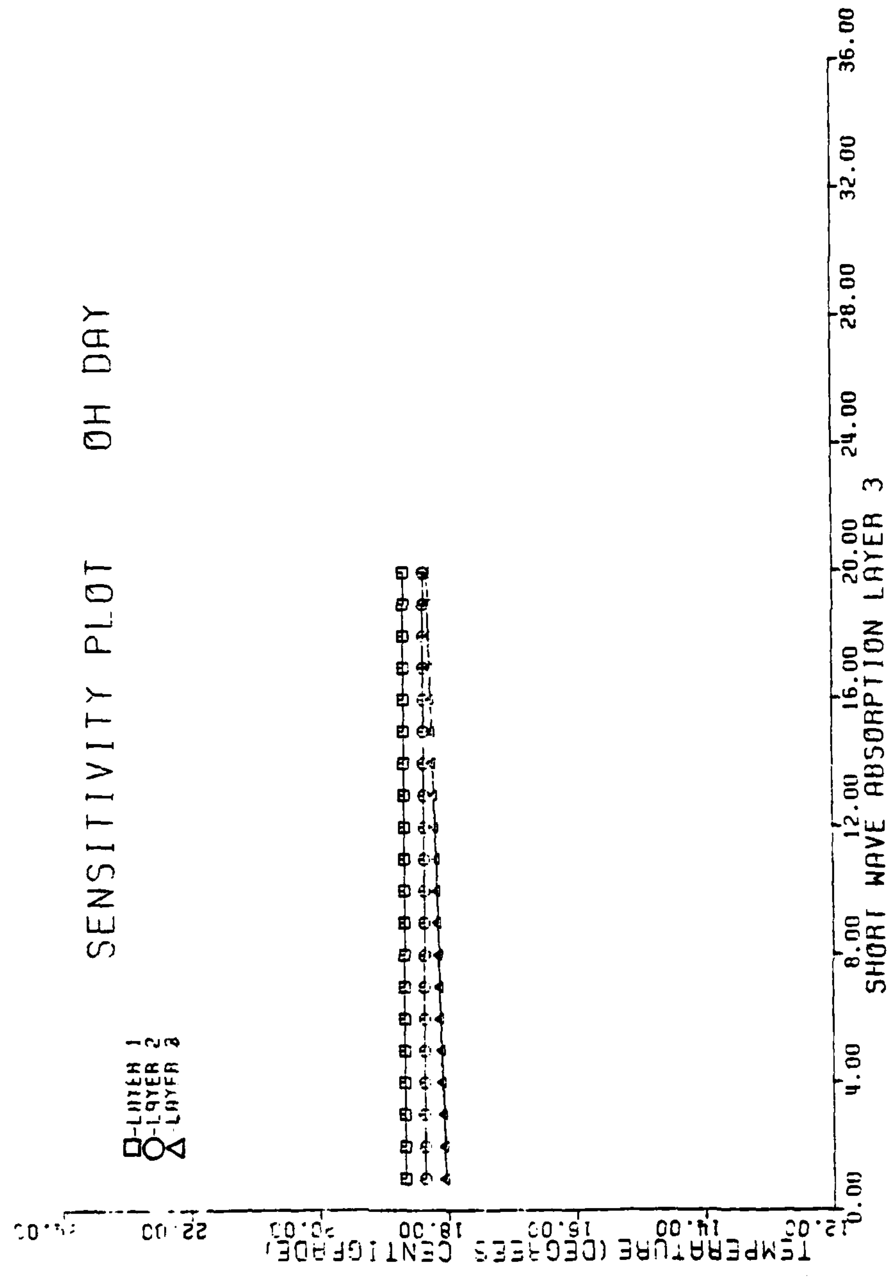
SENSITIVITY PLOT
0H DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
WIND SPEED (CM/SEC)
TEMPERATURE (DEGREES CENTIGRADE)
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280.00
320.00
360.00
12.00
14.00
16.00
18.00
20.00
22.00
24.00

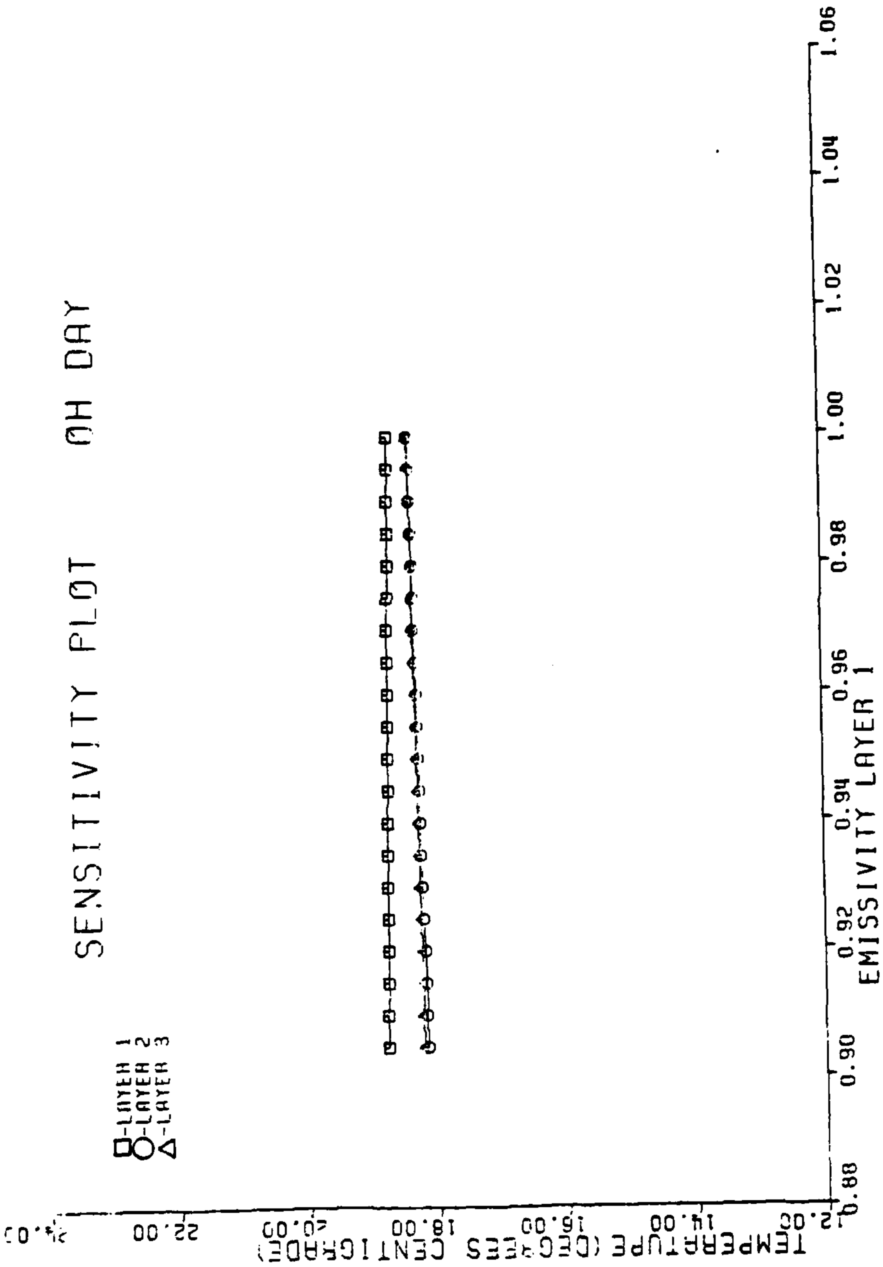

SENSITIVITY PLØT ØH DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
STØMATAL RESISTANCE (MIN/CM)
0.00
0.04
0.08
0.12
0.16
0.20
0.24
0.28
0.32
0.36
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00



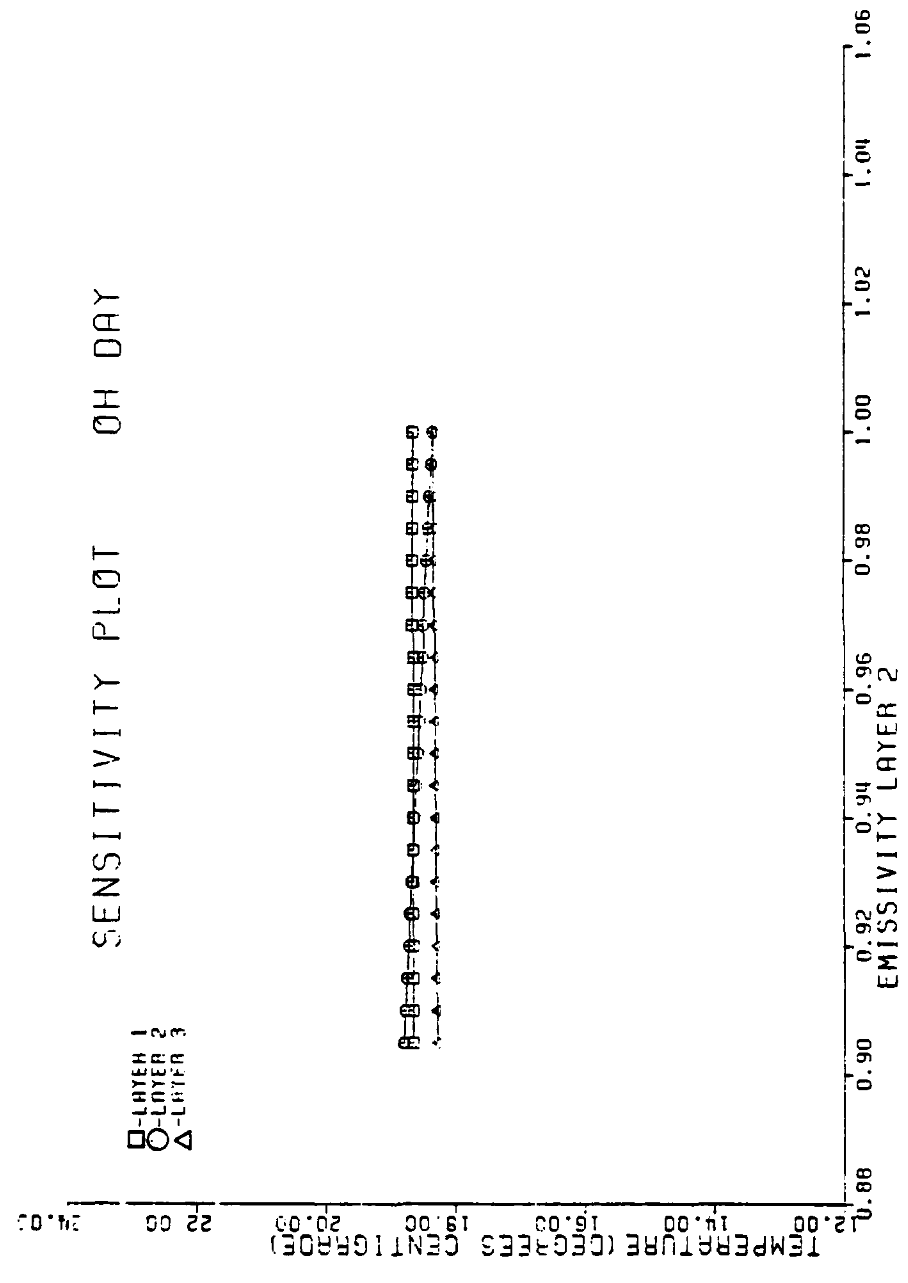
SENSITIVITY PLOT OH DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
SHORT WAVE ABSORPTION LAYER 1
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280.00
320.00
360.00
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00

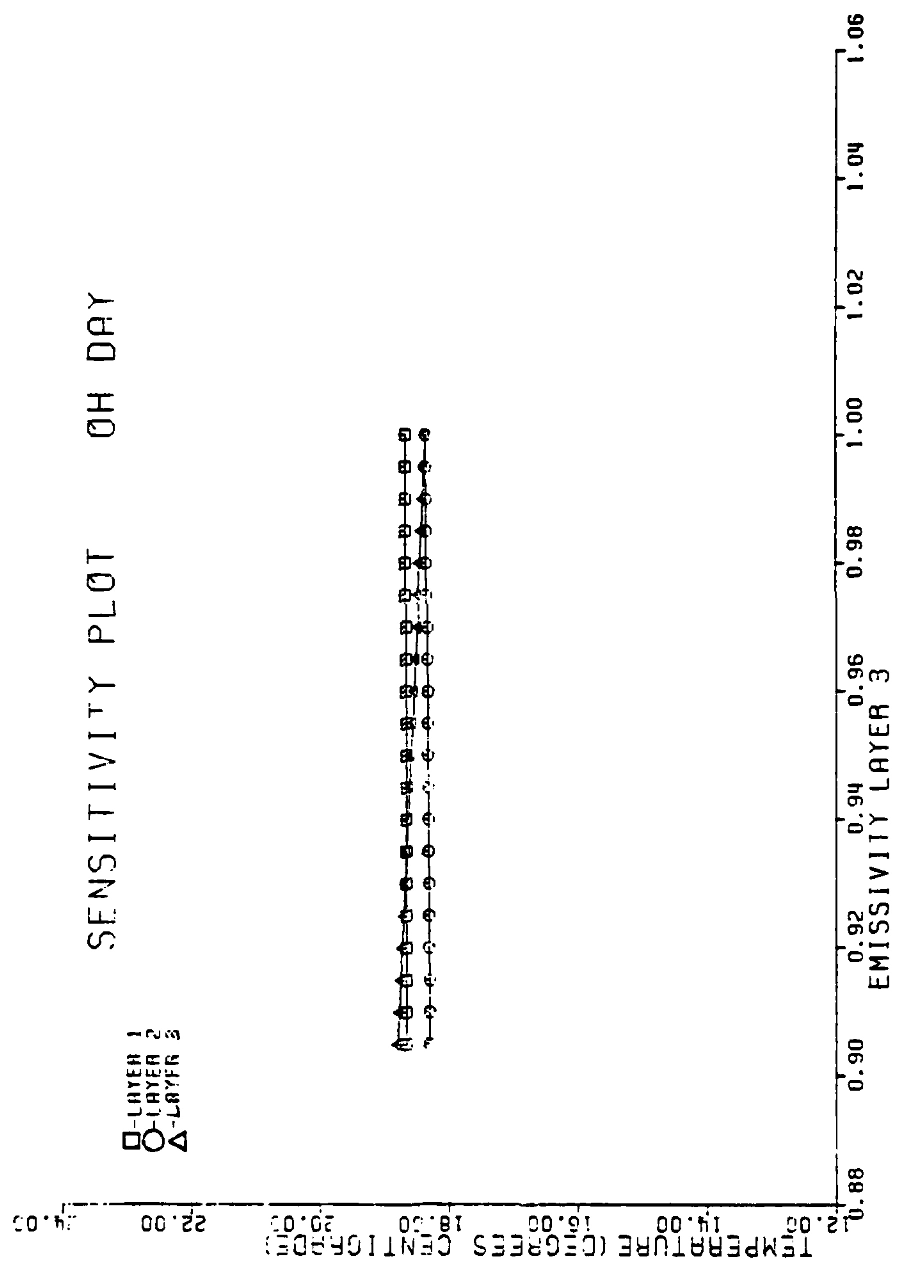

SENSITIVITY PLOT
ØH DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00
SHORT WAVE ABSORPTION LAYER 2
0.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
32.00
36.00


SENSITIVITY PLOT ØH DAY
LAYER 1
LAYER 2
LAYER 3
SHORT WAVE ABSORPTION LAYER 3
0.00 4.00 8.00 12.00 16.00 20.00 24.00 28.00 32.00 36.00
TEMPERATURE (DEGREES CENTIGRADE)
12.00 14.00 16.00 18.00 20.00 22.00 24.00

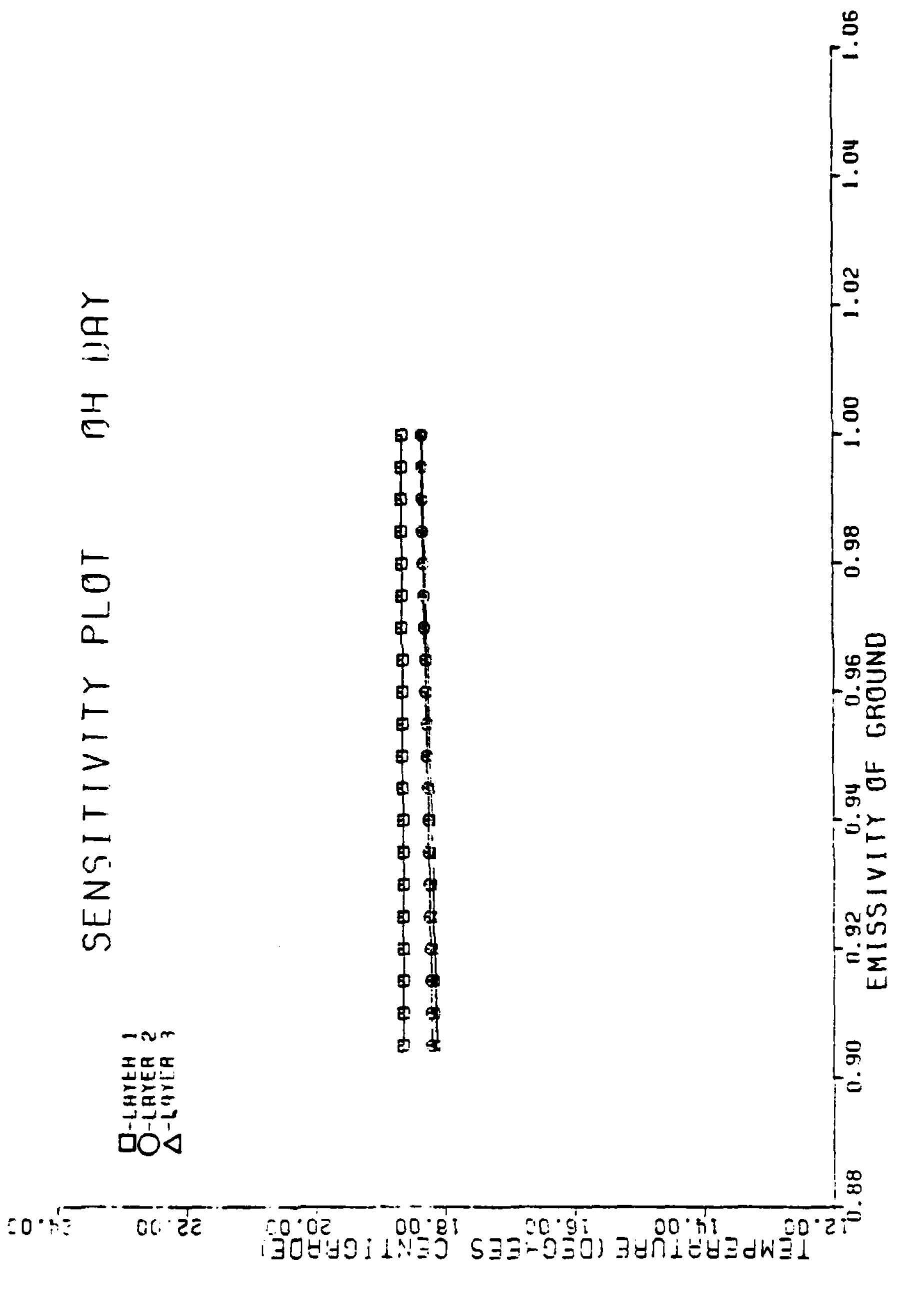


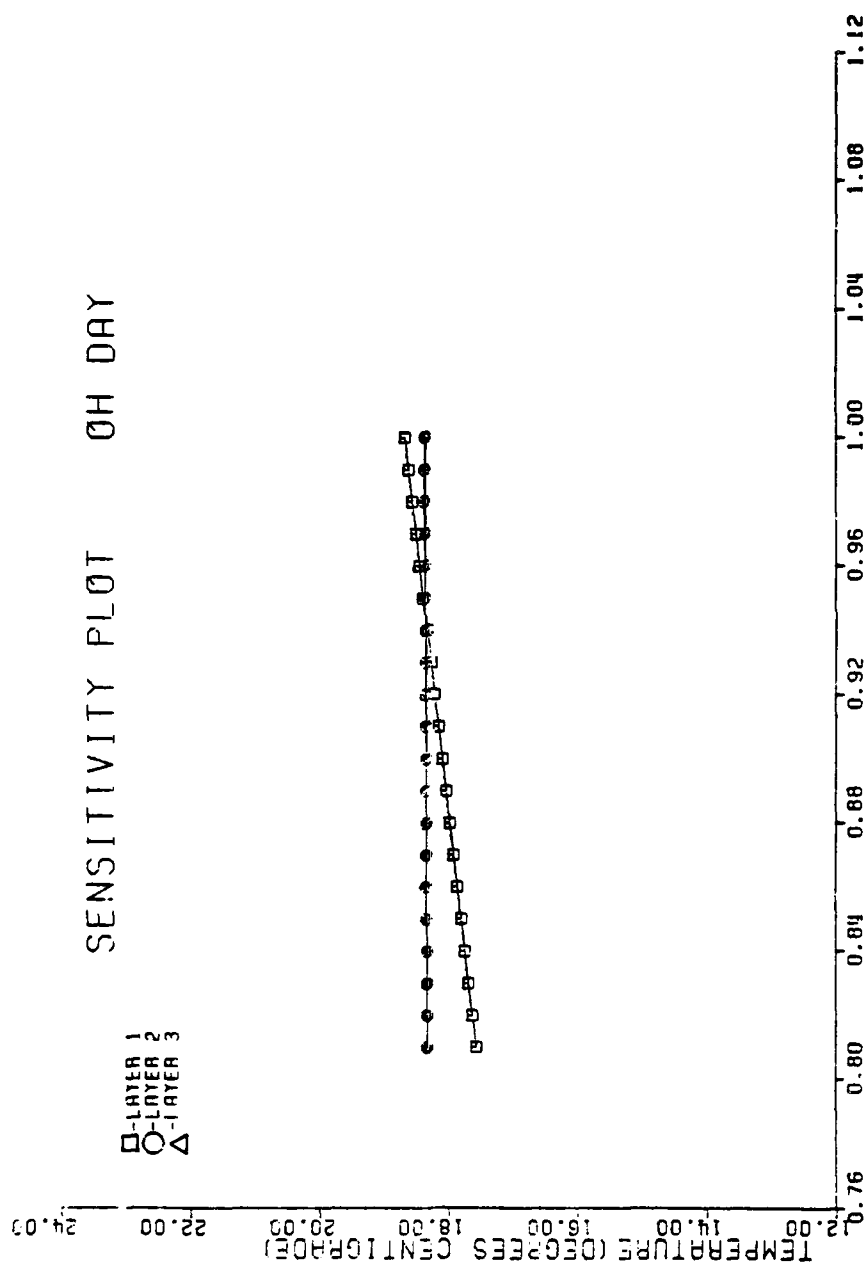
SENSITIVITY PLOT
AH DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06
EMISSIVITY LAYER 1
12.00
14.00
16.00
18.00
20.00
22.00
24.00
TEMPERATURE (DEGREES CENTIGRADE)

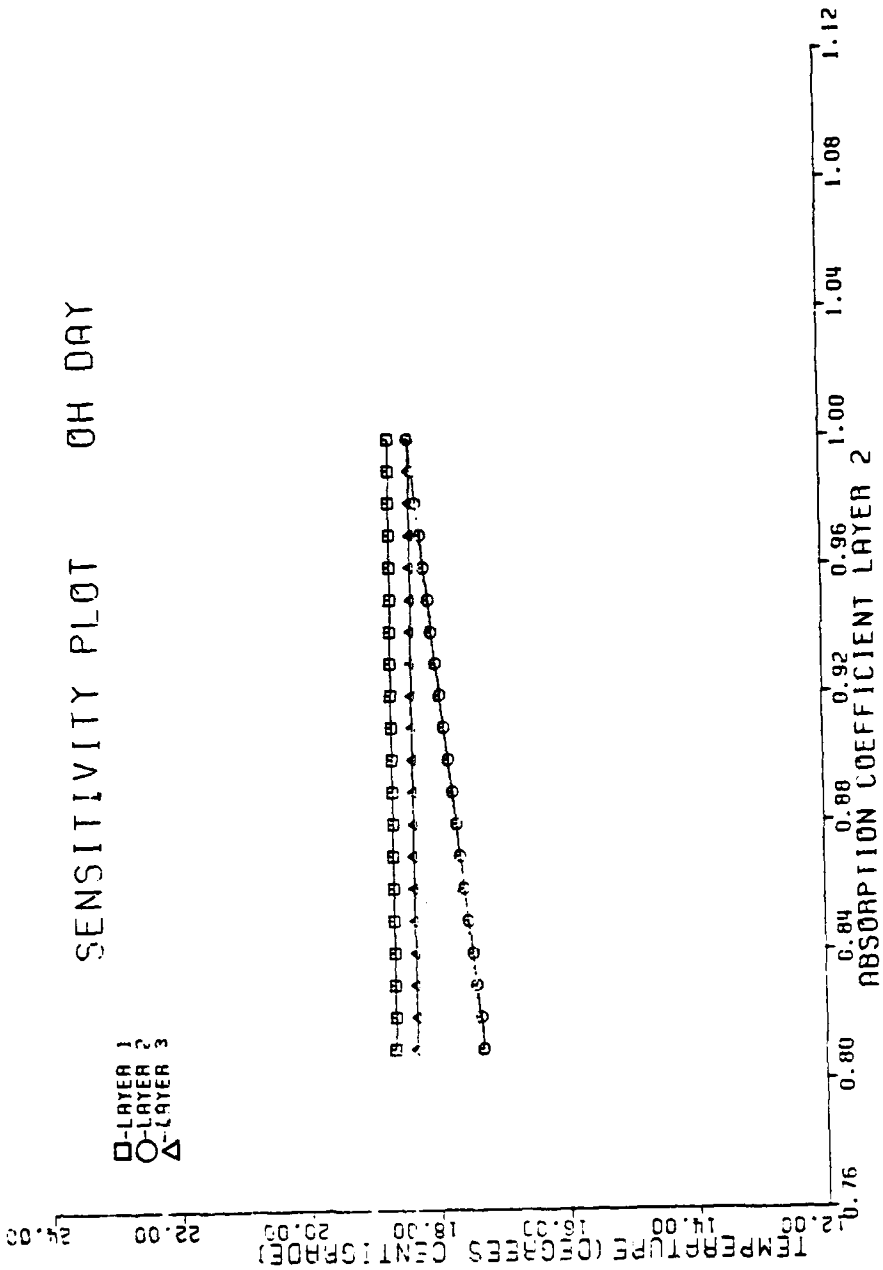

SENSITIVITY PLOT ØH DAY
□-LAYER 1
○-LAYER 2
Δ-LAYER 3
EMISSIVITY LAYER 2
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00



SENSITIVITY PLOT ØH DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
TEMPERATURE(DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00
EMISSIVITY LAYER 3
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06


SENSITIVITY PLØT
□-LAYER 1
○-LAYER 2
△-LAYER 3
EMISSIVITY OF GROUND
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00


SENSITIVITY PLOT ØH DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00
ABSORPTION COEFFICIENT LAYER 1
0.76
0.80
0.84
0.88
0.92
0.96
1.00
1.04
1.08
1.12


SENSITIVITY PLOT 0H DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
ABSORPTION COEFFICIENT LAYER 2
0.76
0.80
0.84
0.88
0.92
0.96
1.00
1.04
1.08
1.12
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00

AD-A106 422 COLORADO STATE UNIV FORT COLLINS DEPT OF FOREST AND --ETC F/G 17/5
THERMAL VEGETATION CANOPY MODEL STUDIES.(U)
AUG 81 J A SMITH, K J RANSON, D NGUYEN DACW39-77-C-0073
UNCLASSIFIED WES/TR/EL-81-6 NL

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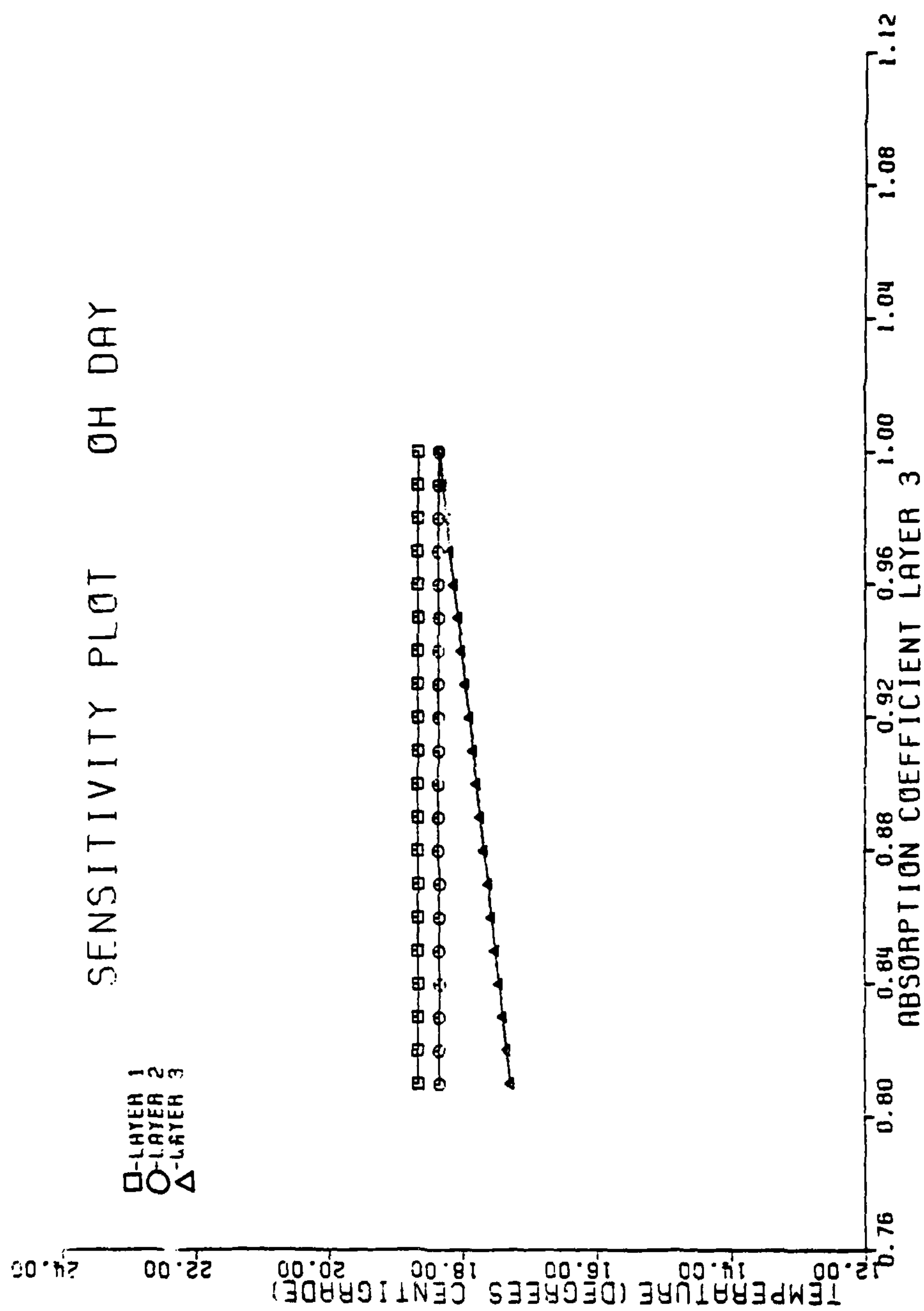
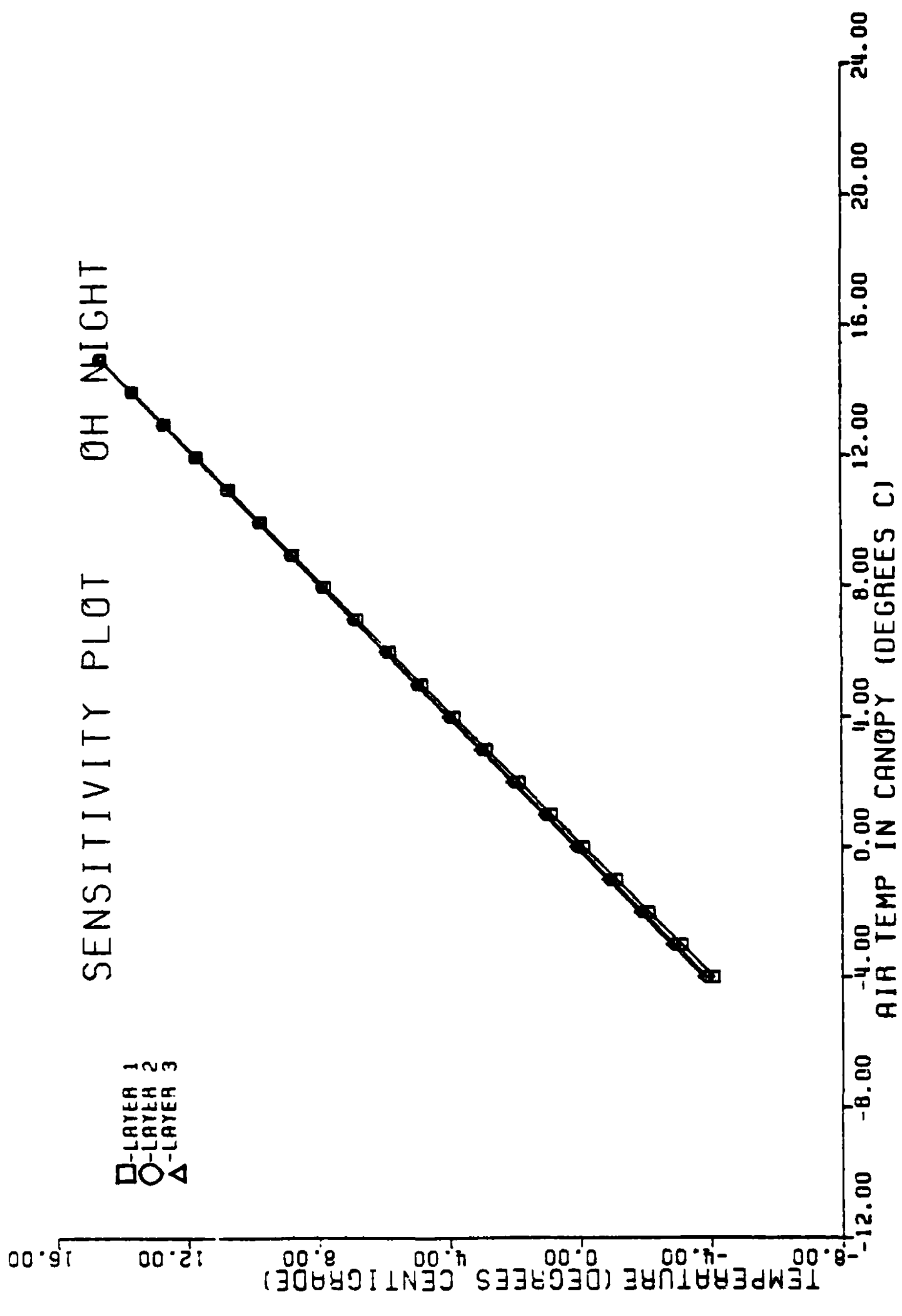
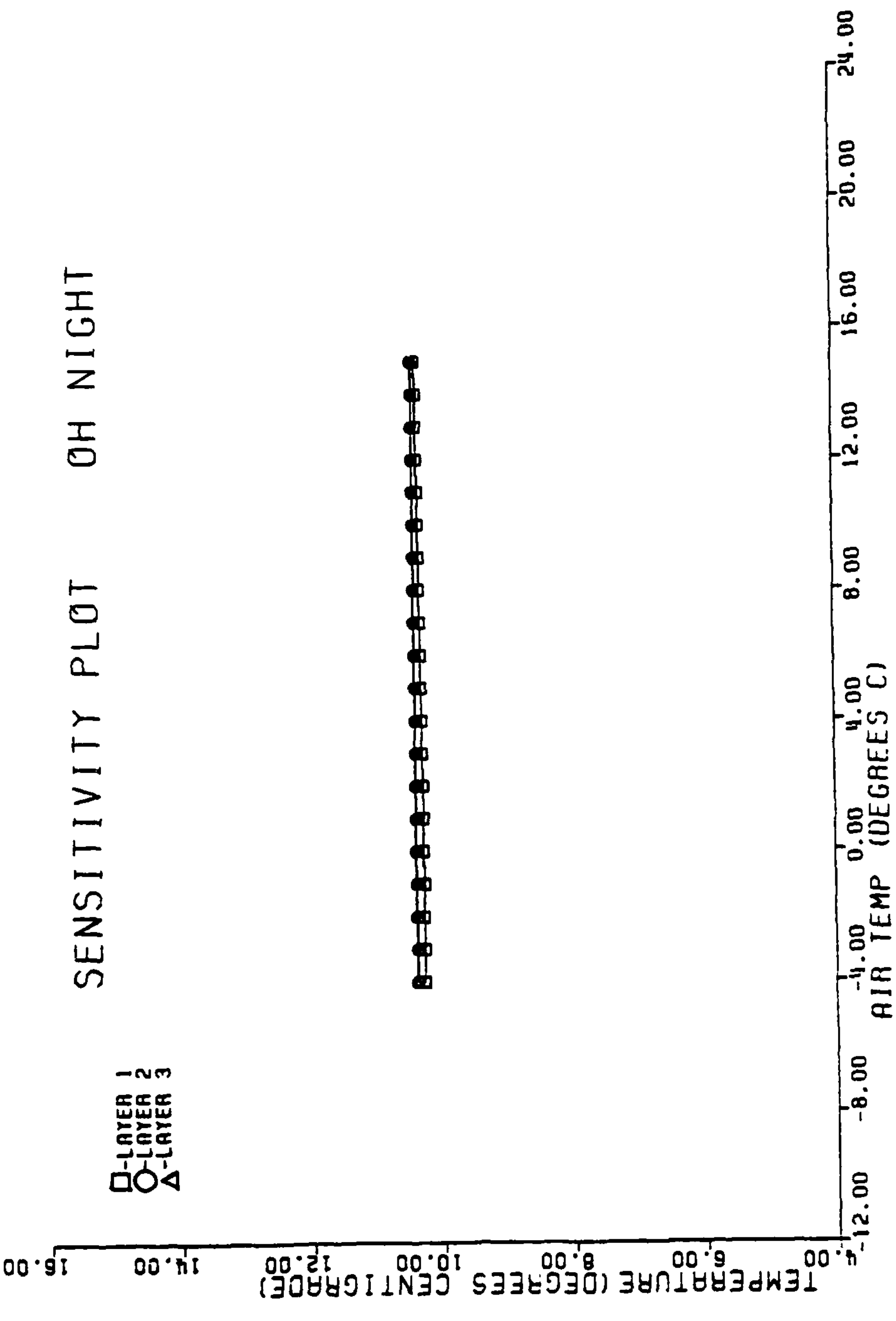


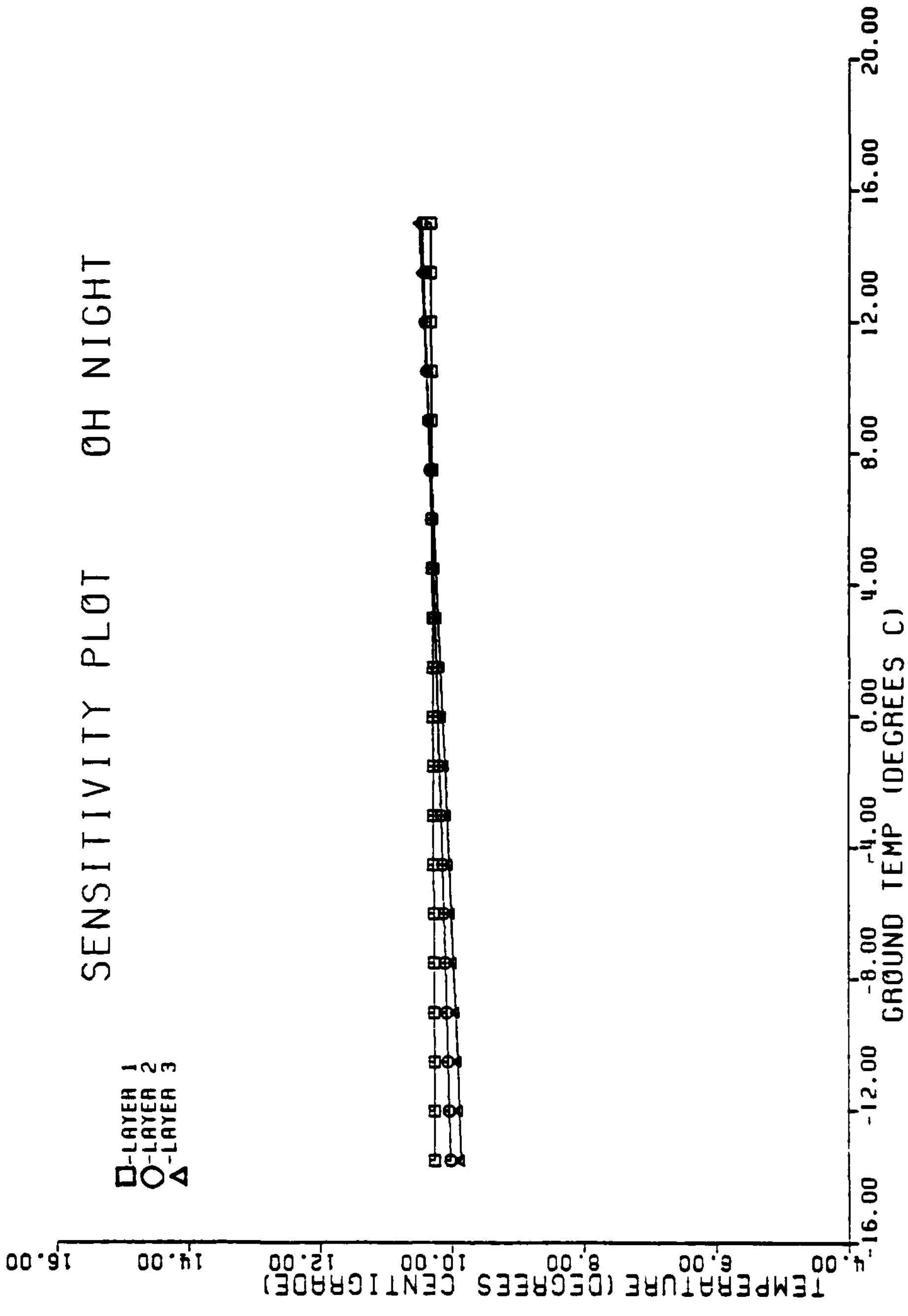
SENSITIVITY PLOT ØH DAY
□-LAYER 1
○-LAYER 2
△-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00
ABSORPTION COEFFICIENT LAYER 3
0.76
0.80
0.84
0.88
0.92
0.96
1.00
1.04
1.08
1.12

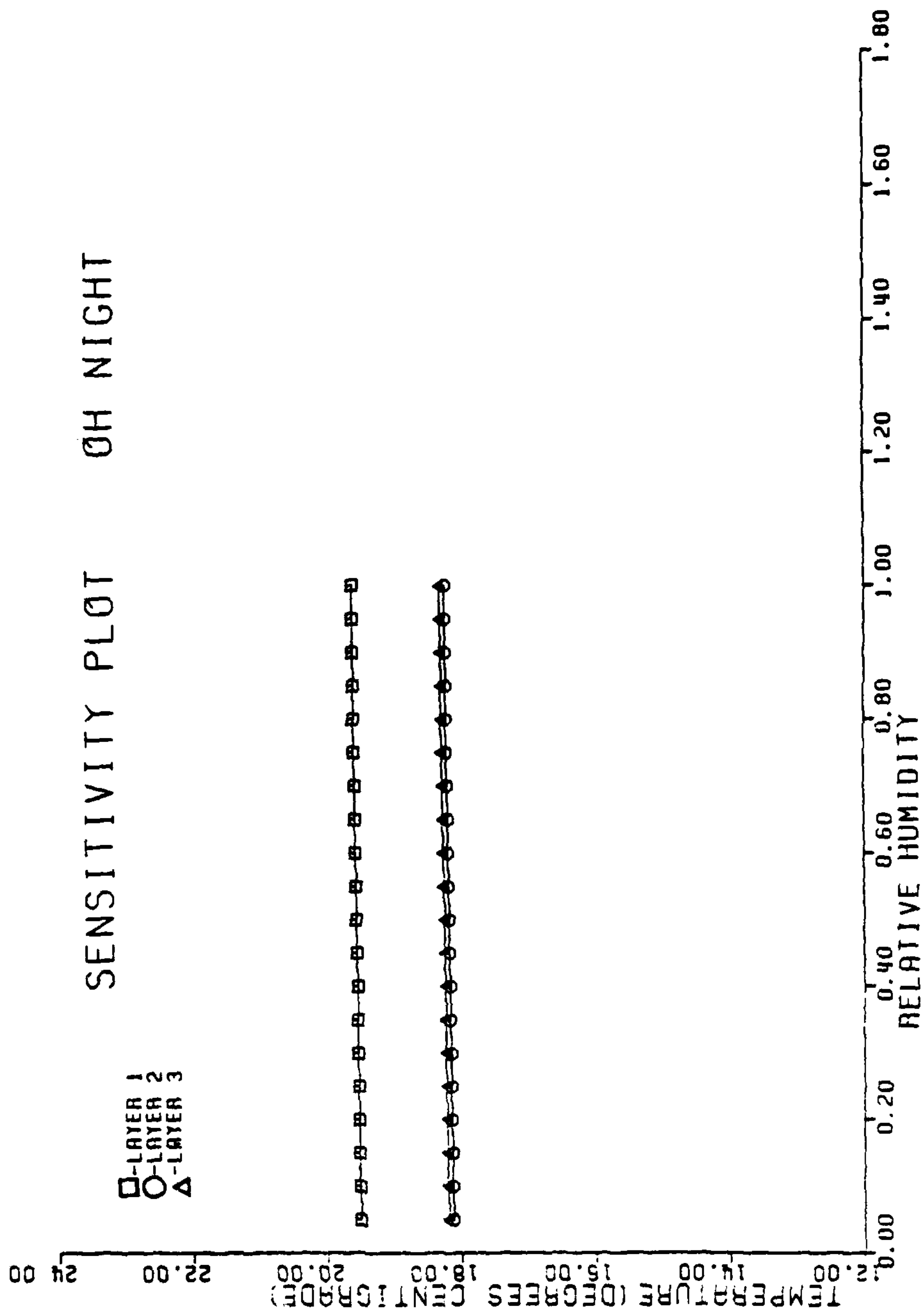
Oak-Hickory Nighttime Sensitivity Plots

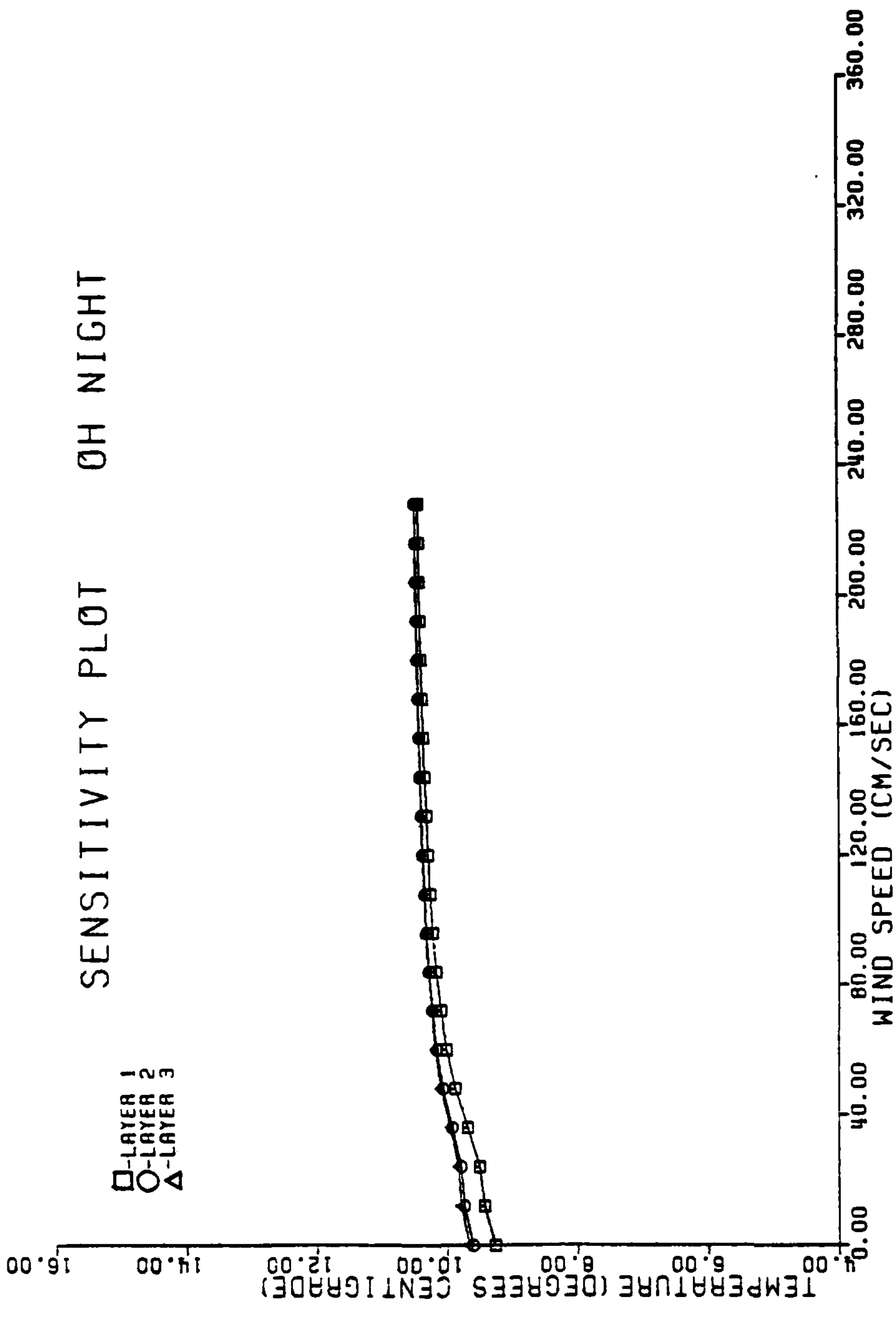


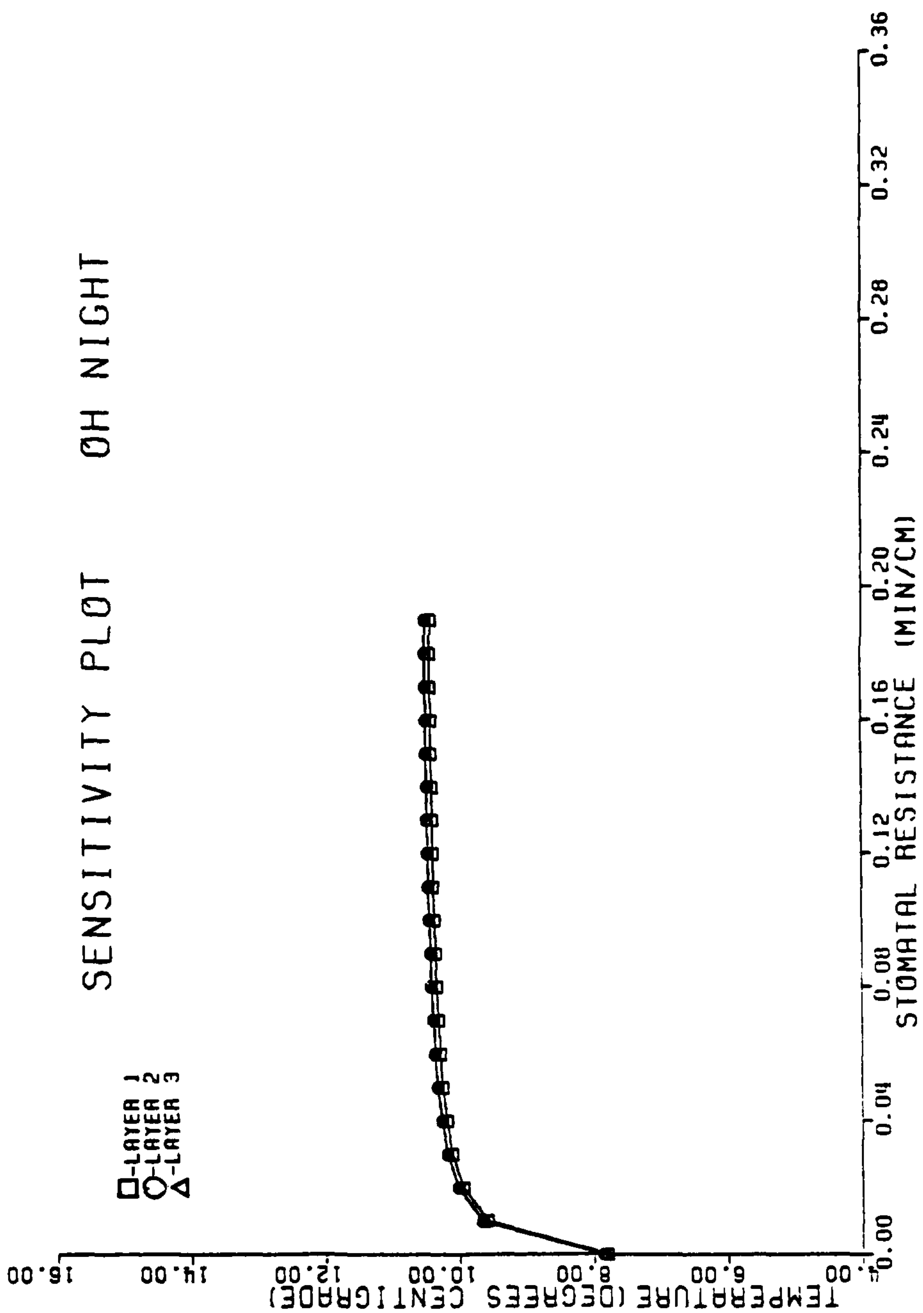
SENSITIVITY PLOT ØH NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
AIR TEMP IN CANØPY (DEGREES C)
TEMPERATURE (DEGREES CENTIGRADE)
-12.00
-8.00
-4.00
0.00
4.00
8.00
12.00
16.00
20.00
24.00
-8.00
-4.00
0.00
4.00
8.00
12.00
16.00


SENSITIVITY PLOT ØH NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
-12.00
-8.00
-4.00
0.00
4.00
8.00
12.00
16.00
20.00
24.00
AIR TEMP (DEGREES C)
4.00
6.00
8.00
10.00
12.00
14.00
16.00
TEMPERATURE (DEGREES CENTIGRADE)

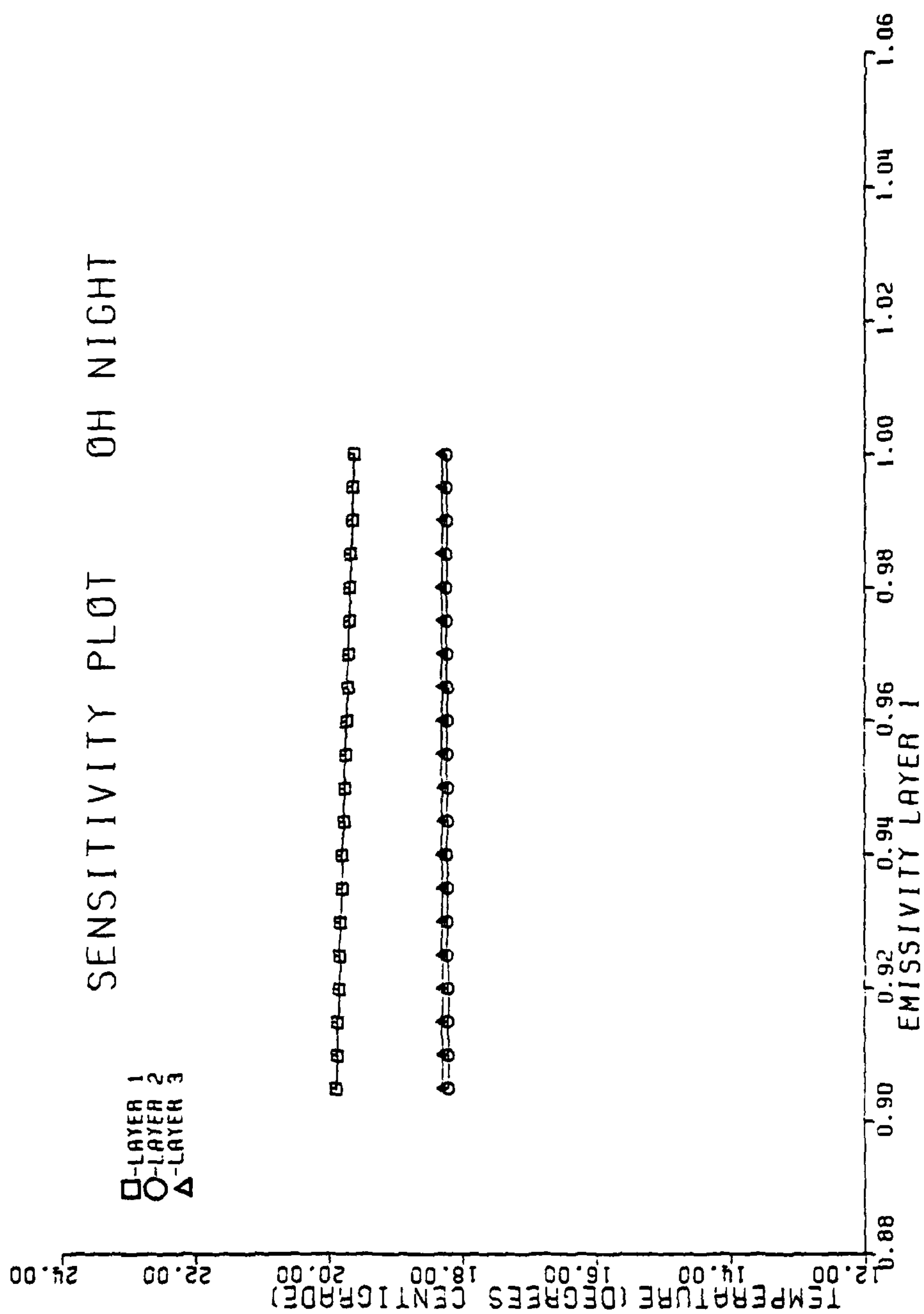

SENSITIVITY PLOT ØH NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
GROUND TEMP (DEGREES C)
-16.00
-12.00
-8.00
-4.00
0.00
4.00
8.00
12.00
16.00
20.00
TEMPERATURE(DEGREES CENTIGRADE)
4.00
6.00
8.00
10.00
12.00
14.00
16.00

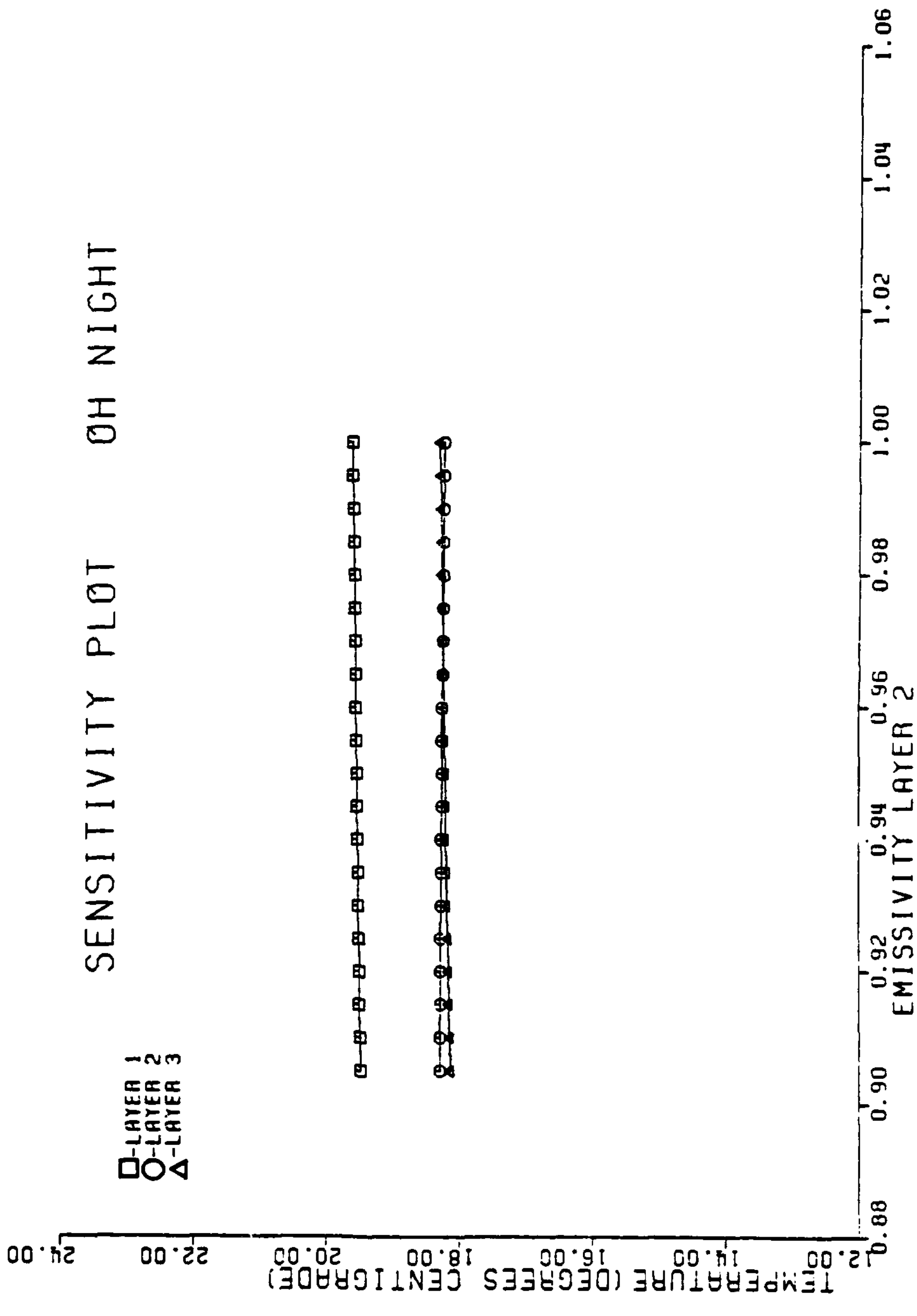

SENSITIVITY PLOT ØH NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
RELATIVE HUMIDITY
TEMPERATURE (DEGREES CENTIGRADE)

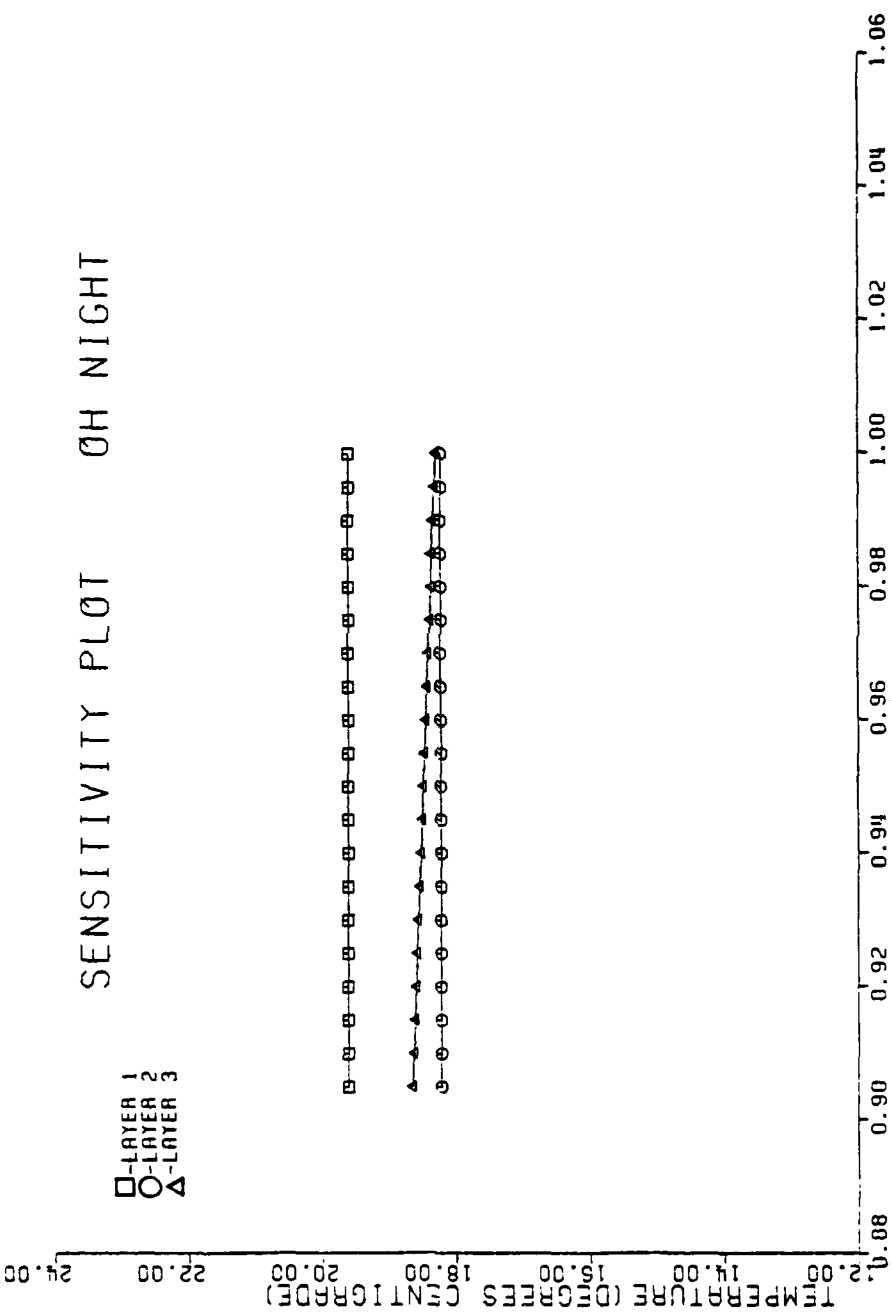

SENSITIVITY PLOT ØH NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
4.00
6.00
8.00
10.00
12.00
14.00
16.00
WIND SPEED (CM/SEC)
0.00
40.00
80.00
120.00
160.00
200.00
240.00
280.00
320.00
360.00

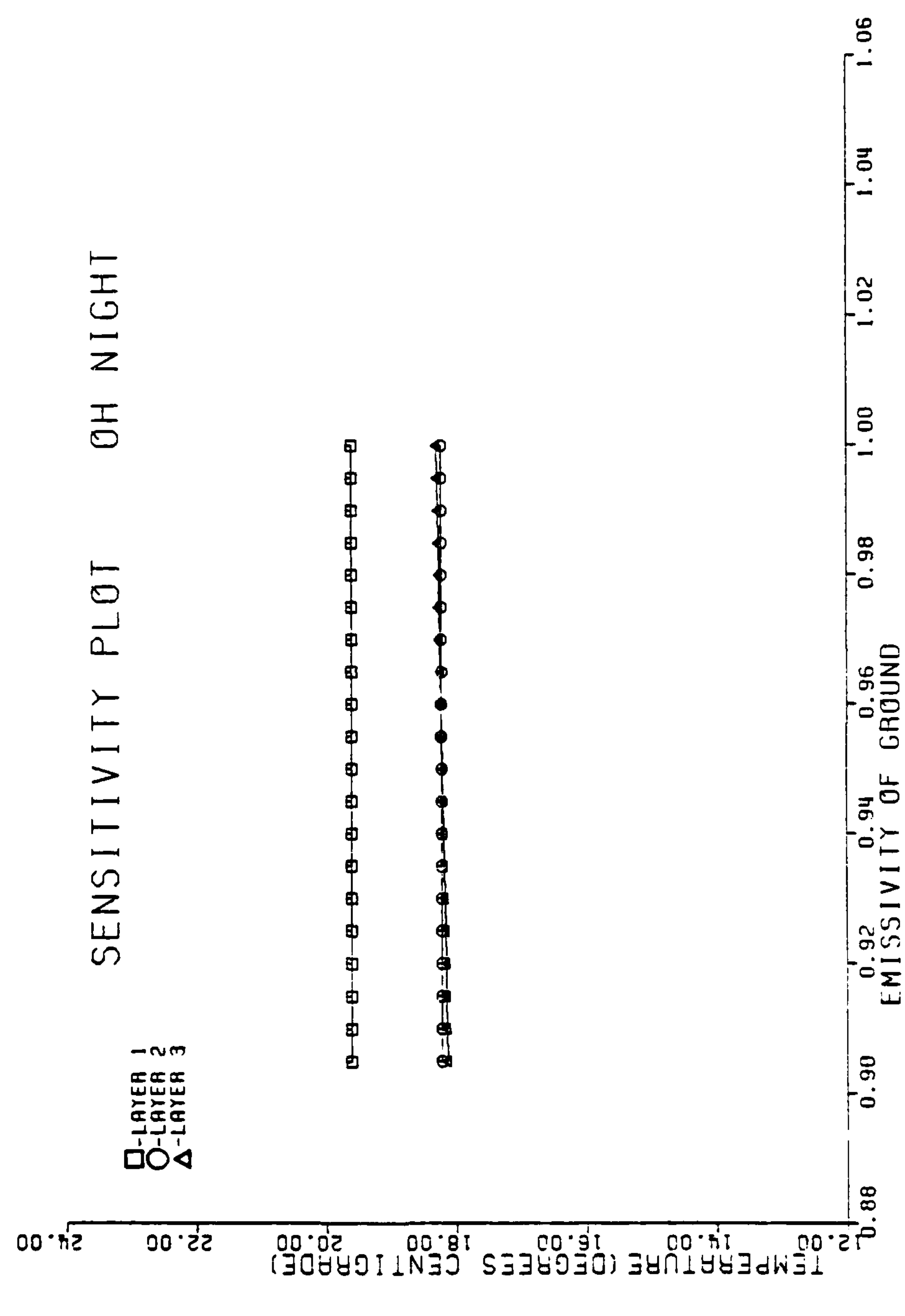


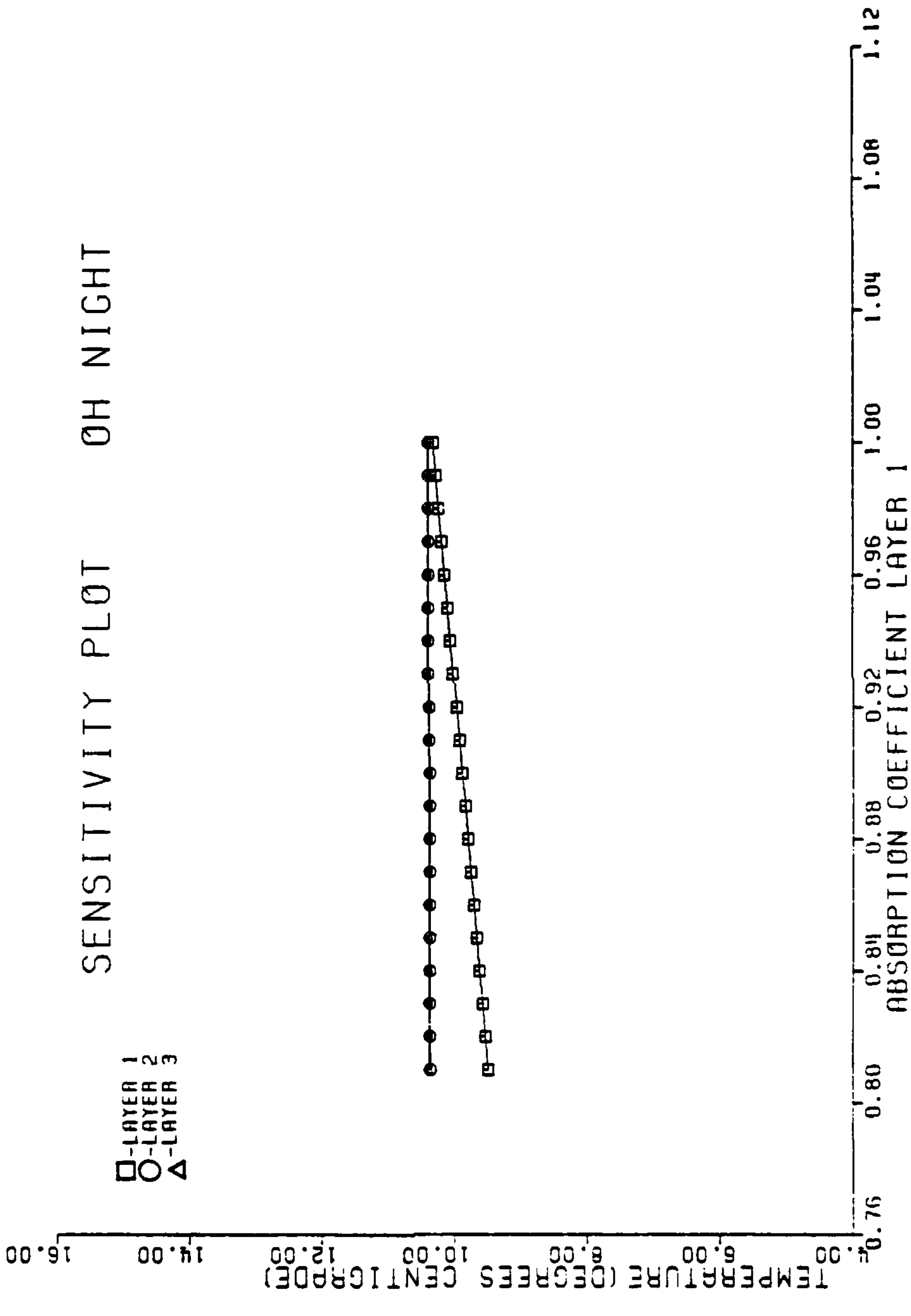
SENSITIVITY PLOT ØH NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
STOMATAL RESISTANCE (MIN/CM)
0.00
0.04
0.08
0.12
0.16
0.20
0.24
0.28
0.32
0.36
TEMPERATURE (DEGREES CENTIGRADE)
4.00
6.00
8.00
10.00
12.00
14.00
16.00

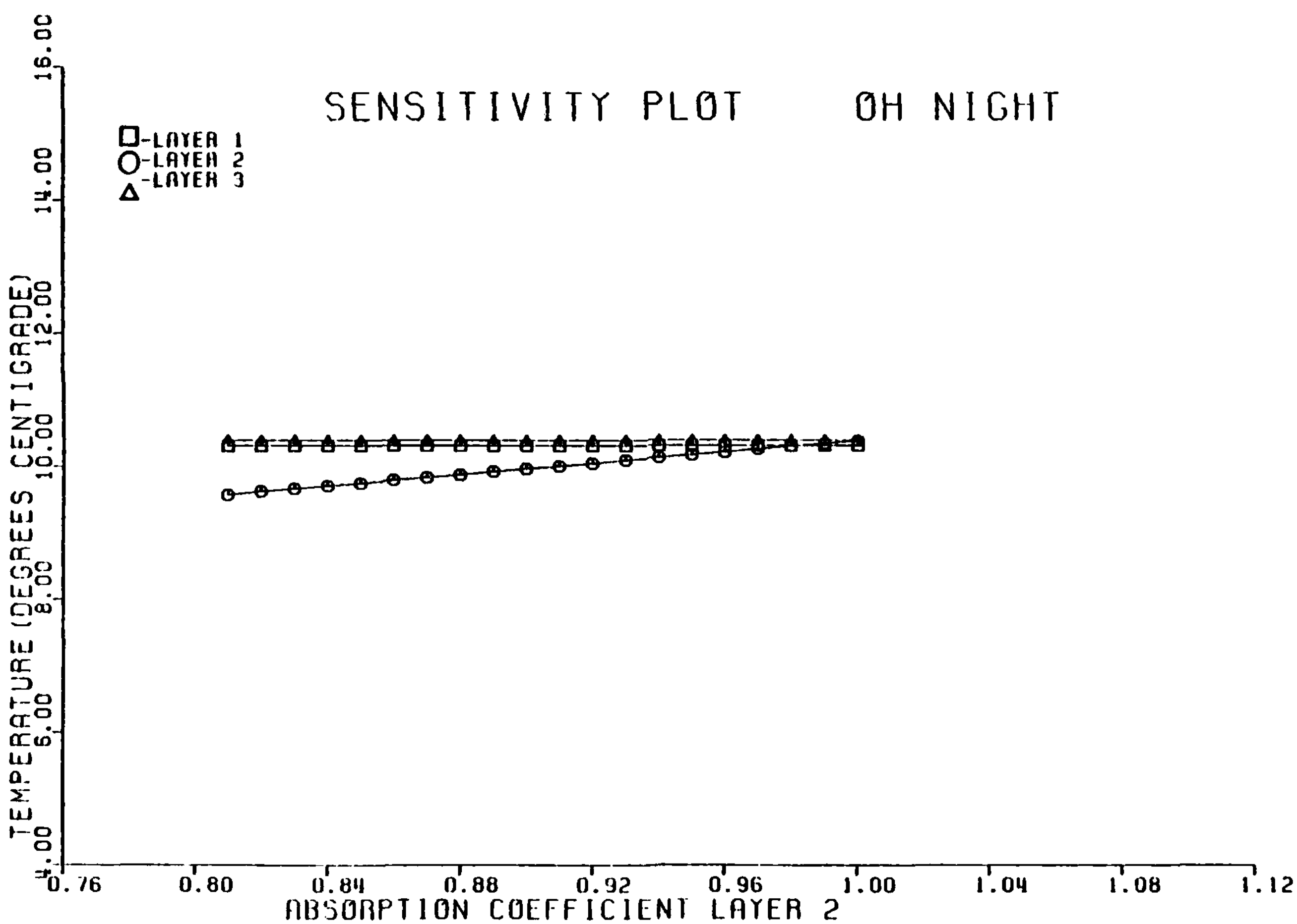

SENSITIVITY PLOT ØH NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00
EMISSIVITY LAYER 1
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06


SENSITIVITY PLOT ØH NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
EMISSIVITY LAYER 2
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06
TEMPERATURE(DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00

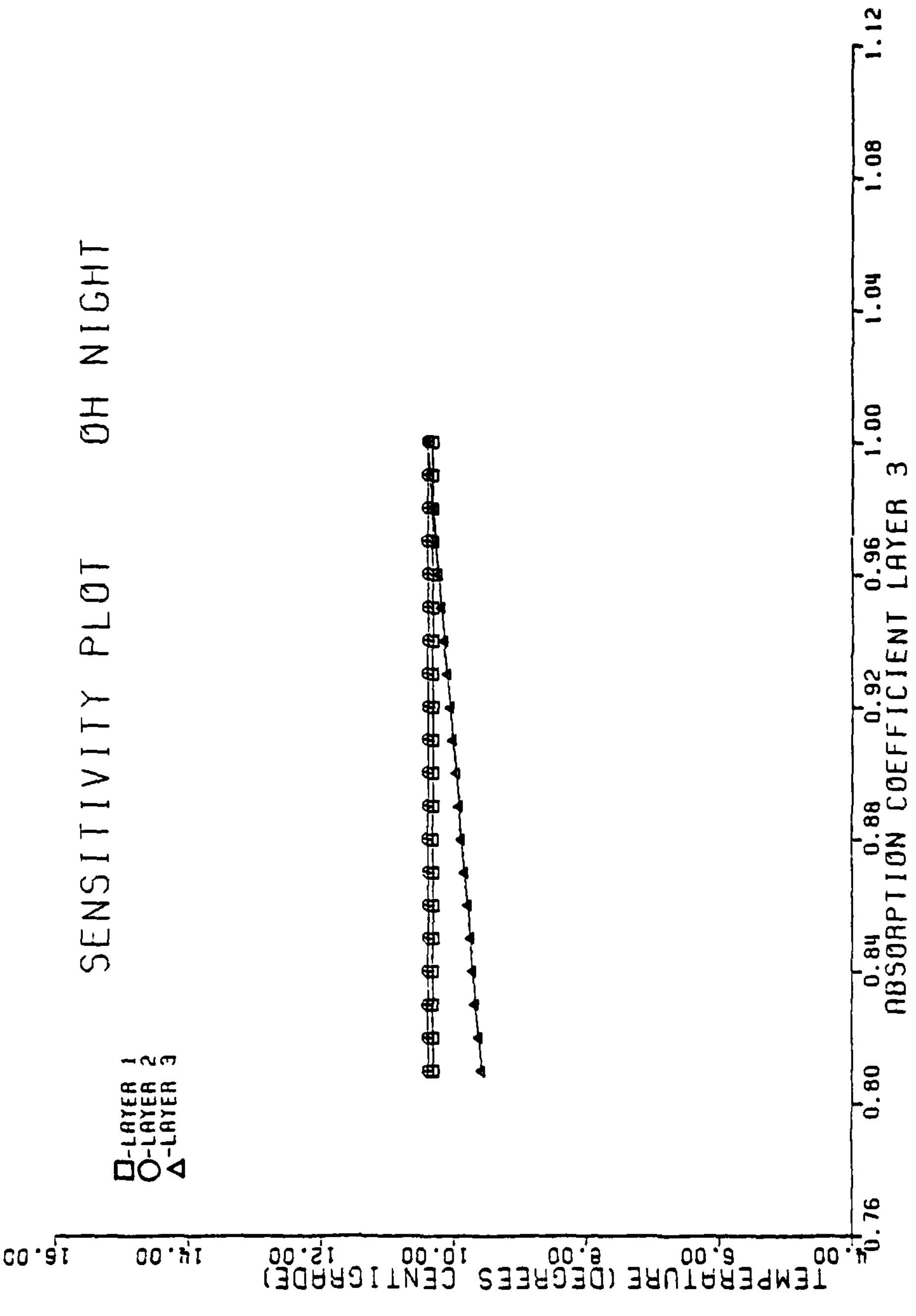

SENSITIVITY PLOT ØH NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
EMISSIVITY LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06
12.00
14.00
16.00
18.00
20.00
22.00
24.00


SENSITIVITY PLØT ØH NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
12.00
14.00
16.00
18.00
20.00
22.00
24.00
EMISSIVITY OF GROUND
0.88
0.90
0.92
0.94
0.96
0.98
1.00
1.02
1.04
1.06


SENSITIVITY PLØT ØH NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
TEMPERATURE (DEGREES CENTIGRADE)
4.00
6.00
8.00
10.00
12.00
14.00
16.00
ABSØRPTION COEFFICIENT LAYER 1
0.76
0.80
0.84
0.88
0.92
0.96
1.00
1.04
1.08
1.12



SENSITIVITY PLOT ØH NIGHT
□-LAYER 1
O-LAYER 2
Δ-LAYER 3
TEMPERATURE(DEGREES CENTIGRADE)
4.00
6.00
8.00
10.00
12.00
14.00
16.00
0.76
0.80
0.84
0.88
0.92
0.96
1.00
1.04
1.08
1.12
ABSORPTION COEFFICIENT LAYER 2


SENSITIVITY PLOT ØH NIGHT
□-LAYER 1
○-LAYER 2
△-LAYER 3
ABSORPTION COEFFICIENT LAYER 3
0.76
0.80
0.84
0.88
0.92
0.96
1.00
1.04
1.08
1.12
TEMPERATURE (DEGREES CENTIGRADE)
4.00
6.00
8.00
10.00
12.00
14.00
16.00

APPENDIX D: SUPPORTING VALIDATION DATA

Cedar River, Douglas-Fir

CANOPY GEOMETRY INPUT DATA FOR DOUGLAS-FIR

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
1.50	5.30	1.00

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

FOLIAGE ANGLE DISTRIBUTION

INCLINATION ANGLE	PROBABILITY OF OCCURRENCE LAYER 1	LAYER 2	LAYER 3
0.0	.088	.093	.089
5.0	.078	.079	.078
10.0	.079	.080	.079
15.0	.077	.078	.078
20.0	.084	.084	.084
25.0	.077	.077	.077
30.0	.081	.080	.080
35.0	.059	.059	.059
40.0	.088	.087	.088
45.0	.063	.062	.063
50.0	.062	.061	.062
55.0	.045	.043	.044
60.0	.044	.042	.043
65.0	.029	.029	.029
70.0	.024	.024	.024
75.0	.013	.013	.013
80.0	.007	.007	.007
85.0	.003	.003	.003
90.0	0.000	0.000	0.000

THERMAL MODEL INPUT DATA FOR DOUGLAS-FIR

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

	ZENITH ANGLE								
	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	.9974	.8703	.7697	.7214	.6994	.6900	.6865	.6856	.6855
LAYER 2	.0026	.1296	.2289	.2753	.2960	.3047	.3079	.3088	.3089
LAYER 3	.0000	.0001	.0009	.0018	.0025	.0028	.0029	.0029	.0029
GROUND	.0000	.0000	.0006	.0015	.0022	.0025	.0027	.0027	.0027

LONG WAVE TRANSFER MATRIX

	FROM				
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.4599	1.0731	.4540	.0031	.0027
LAYER 2	.0267	.0661	1.8071	.0507	.0421
LAYER 3	.0022	.0052	.5887	.8008	.5960

AVERAGE SHORTWAVE ABSORPTION COEFFICIENTS

LAYER 1	LAYER 2	LAYER 3
.3890	.0190	.0280

STOMATAL RESISTANCE

.66 (MIN/CM)

ENVIRONMENTAL INPUT DATA

CEDAR RIVER, WASHINGTON 4 AUGUST 1979

TIME (HOURS)	AIR TEMP (DEG C)	GRND TEMP (DEG C)	WIND SPEED (M/SEC)	REL HUM	GLOBAL SUR (W/M**2)
100	9.8	12.4	1.0	.99	0.00
200	9.3	12.0	1.0	1.00	0.00
300	8.7	11.5	.9	1.00	0.00
400	8.2	11.1	1.0	1.00	0.00
500	7.5	10.6	.9	1.00	0.00
600	7.0	10.2	.9	1.00	1.80
700	7.2	9.7	.7	1.00	69.20
800	9.2	9.7	.6	.99	227.80
900	11.8	10.3	.5	.94	445.70
1000	13.8	11.3	1.5	.89	621.60
1100	15.7	13.0	1.8	.87	772.60
1200	16.8	14.3	1.9	.85	814.50
1300	18.3	15.5	1.9	.84	847.70
1400	19.5	16.2	2.1	.83	686.80
1500	20.5	17.0	2.2	.81	835.70
1600	21.2	17.9	2.7	.81	770.20
1700	21.3	18.2	3.0	.81	618.40
1800	21.8	18.8	3.1	.80	493.90
1900	21.2	17.7	2.5	.78	289.90
2000	20.5	17.4	2.0	.78	115.40
2100	17.4	16.7	.8	.81	7.50
2200	14.6	15.7	1.1	.87	0.00
2300	14.6	14.8	1.5	.88	0.00
2400	14.4	14.5	1.5	.88	0.00

ENVIRONMENTAL INPUT DATA

CEDAR RIVER, WASHINGTON 5 AUGUST 1979

TIME (HOURS)	AIR TEMP (DEG C)	GRND TEMP (DEG C)	WIND SPEED (M/SEC)	REL HUM	GLOBAL SUR (W/M**2)
100	13.6	14.4	1.1	.92	0.00
200	13.0	14.2	.4	.93	0.00
300	12.7	14.2	.5	.94	0.00
400	12.6	14.1	1.1	.93	0.00
500	12.0	14.0	1.2	.93	0.00
600	11.3	13.7	.9	.94	1.60
700	11.0	13.4	.6	.95	30.40
800	11.2	13.3	.6	.94	64.50
900	11.6	13.4	1.2	.93	111.90
1000	12.2	13.5	1.2	.91	154.60
1100	13.0	13.7	1.2	.90	228.20
1200	14.6	14.3	1.3	.88	659.60
1300	16.7	15.2	1.6	.85	719.30
1400	17.0	15.8	2.0	.84	370.00
1500	17.3	16.0	1.3	.84	366.60
1600	18.6	16.4	1.3	.84	659.40
1700	18.6	16.8	1.4	.83	399.20
1800	19.4	16.8	1.8	.82	388.00
1900	19.4	16.9	2.3	.82	301.30
2000	18.6	16.6	1.2	.83	110.90
2100	15.7	16.0	.7	.87	9.20
2200	13.6	15.0	1.0	.93	0.00
2300	12.5	14.2	.9	.95	0.00
2400	12.4	13.7	1.0	.96	0.00

Walker Branch, Oak-Hickory

CANOPY GEOMETRY INPUT DATA FOR OAK HICKORY

LEAF AREA INDEX

LAYER 1	LAYER 2	LAYER 3
3.40	.80	.40

CANOPY DENSITY PARAMETERS

LAYER 1	LAYER 2	LAYER 3
.10	.10	.10

FOLIAGE ANGLE DISTRIBUTION

INCLINATION ANGLE	PROBABILITY OF OCCURRENCE LAYER 1	LAYER 2	LAYER 3
0.0	.066	.117	.014
5.0	.067	.155	.233
10.0	.084	.129	.120
15.0	.086	.177	.157
20.0	.050	.064	.053
25.0	.098	.135	.154
30.0	.084	.081	.100
35.0	.076	.037	.047
40.0	.063	.040	0.000
45.0	.087	.019	.010
50.0	.040	.015	0.000
55.0	.043	.019	0.000
60.0	.031	.007	0.000
65.0	.033	.002	0.000
70.0	.024	.002	0.000
75.0	0.000	0.000	0.000
80.0	0.000	0.000	0.000
85.0	0.000	0.000	0.000
90.0	0.000	0.000	0.000

THERMAL MODEL INPUT DATA FOR OAK HICKORY

GEOMETRICAL VIEW ANGLE FACTOR MATRIX

	ZENITH ANGLE								
	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0
LAYER 1	1.0000	.9947	.9774	.9642	.9573	.9545	.9536	.9536	.9536
LAYER 2	0.0000	.0018	.0068	.0105	.0124	.0131	.0134	.0134	.0134
LAYER 3	0.0000	.0011	.0047	.0075	.0090	.0096	.0098	.0098	.0098
GROUND	0.0000	.0023	.0110	.0178	.0213	.0227	.0232	.0232	.0232

LONG WAVE TRANSFER MATRIX

	FROM				
TO	SKY	LAYER 1	LAYER 2	LAYER 3	GROUND
LAYER 1	.1595	1.6741	.0470	.0338	.0788
LAYER 2	.0281	.7914	.3539	.2589	.5607
LAYER 3	.0201	.5442	.2574	.3496	.8217

AVERAGE SHORTWAVE ABSORPTION COEFFICIENTS

LAYER 1	LAYER 2	LAYER 3
.089	.042	.040

STOMATAL RESISTANCE

.07 (MIN/CM)

ENVIRONMENTAL INPUT DATA

WALKER BRANCH, TENNESSEE 18 AUGUST 1979

TIME (HOURS)	AIR TEMP (DEG C)	GRND TEMP (DEG C)	WIND SPEED (M/SEC)	REL HUM	GLOBAL SWR (W/M**2)
100	19.5	19.5	3.1	.83	0.00
200	19.3	19.5	3.2	.85	0.00
300	18.8	19.4	2.8	.87	0.00
400	18.3	19.3	2.3	.91	0.00
500	18.0	19.2	2.7	.94	0.00
600	17.7	19.1	2.4	.96	0.00
700	17.9	19.1	3.0	.96	38.20
800	19.3	19.2	3.0	.93	175.40
900	21.0	19.3	2.4	.88	329.90
1000	22.4	19.5	4.3	.84	445.70
1100	24.4	19.9	3.5	.77	661.90
1200	26.0	20.4	3.6	.71	681.10
1300	27.1	20.7	2.8	.65	614.00
1400	28.2	21.0	2.9	.64	770.10
1500	29.2	21.4	2.8	.61	787.00
1600	28.5	21.6	2.8	.61	531.70
1700	28.5	21.6	2.7	.62	474.00
1800	27.7	21.7	2.4	.65	269.10
1900	26.2	21.6	2.3	.70	85.00
2000	24.9	21.4	2.2	.75	2.90
2100	24.3	21.3	2.9	.76	0.00
2200	23.5	21.2	3.0	.78	0.00
2300	22.8	21.0	3.2	.80	0.00
2400	22.1	20.7	3.4	.83	0.00

ENVIRONMENTAL INPUT DATA

WALKER BRANCH, TENNESSEE 19 AUGUST 1979

TIME (HOURS)	AIR TEMP (DEG C)	GRND TEMP (DEG C)	WIND SPEED (M/SEC)	REL HUM	GLOBAL SWR (W/M**2)
100	22.1	20.7	3.4	.85	0.00
200	21.5	20.6	3.5	.91	0.00
300	21.1	20.6	3.2	.92	0.00
400	20.4	20.5	2.4	.99	0.00
500	19.8	20.3	2.6	1.00	0.00
600	19.6	20.3	1.8	1.00	0.00
700	19.1	20.2	1.5	1.00	22.80
800	20.8	20.3	1.7	1.00	182.80
900	23.8	20.4	1.5	.91	365.00
1000	26.1	20.6	2.4	.80	582.10
1100	27.8	21.0	2.5	.73	751.60
1200	29.2	21.5	2.8	.69	753.60
1300	30.4	21.8	2.2	.63	827.50
1400	31.7	22.2	2.1	.61	917.40
1500	31.3	22.6	2.1	.60	778.00
1600	31.1	22.8	2.1	.61	620.40
1700	30.2	22.8	2.5	.63	457.60
1800	29.5	22.8	1.7	.67	251.70
1900	27.9	22.7	1.9	.74	81.40
2000	26.2	22.4	2.6	.71	2.60
2100	25.9	22.2	2.1	.69	0.00
2200	25.1	22.0	2.3	.74	0.00
2300	24.3	22.9	2.0	.81	0.00
2400	22.1	21.7	2.0	.81	0.00

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Thermal vegetation canopy model studies : final report / by J.A. Smith ... [et al]. (Department of Wood Science, College of Forestry and Natural Resources, Colorado State University). -- Vicksburg, Miss. : U.S. Army Engineer Waterways Experiment Station ; Springfield, Va. : available from NTIS, [1981].

213 p. in various pagings : ill. ; 27 cm. -- (Technical report / U.S. Army Engineer Waterways Experiment Station ; EL-81-6)

Cover title.

"August 1981."

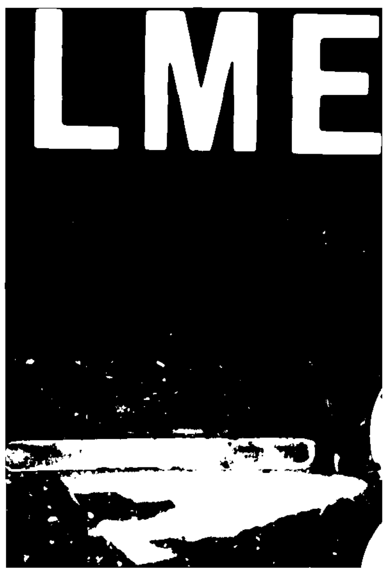
"Prepared for Headquarters, Department of the Army, under Project No. 4A762730AT42, Task A4, Work Unit 003 (Contract No. DACW 39-77-C-0073)."

"Monitored by Environmental Laboratory, U.S. Army Engineer Waterways Experiment Station."

Bibliography: p. 44-45.

Thermal vegetation canopy model studies : ... 1981.
(Card 2)

1. Computer simulation. 2. Infra-red detectors. 3. Remote sensing. 4. Thermal analysis. 5. Vegetation classification. I. Smith, J.A. II. Colorado State University. College of Forestry and Natural Resources. III. United States. Department of the Army. IV. U.S. Army Engineer Waterways Experiment Station. Environmental Laboratory. IV. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; EL-81-6.
TA7.W34 no.EL-81-6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